Cross-strike discontinuities and kinematic linkages within the Moine and Cantabrian thrust belts

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Abstract

Abrupt lateral changes in thrust geometry occur in many mountain-building fold-thrust belts. Whilst many works have dealt with palinspastic reconstructions and transport-direction-parallel balanced cross-sections, far fewer show a full three-dimensional architecture, or examine how lateral variations in thrust architecture can be linked via cross-strike discontinuities or transverse zones. Systematic alignments of lateral structures are suggested to be related to kinematic responses to irregularities generated across pre-existing, sometimes reactivated, sub-décollement basement faults, pre-thrusting cover strata deformation above basement faults, development of duplex structures / antiformal stacks, and / or along-strike variations in mechanical stratigraphy.

New cross-strike discontinuity / transverse zone identification methodologies developed within this research incorporating thrust ramp-flat alignment analyses and branch-point, cut-off point and fault-tip point analyses, together with a variety of previously utilised identification techniques, allow spatial alignments of lateral structures to be determined. New methodologies help to better characterise the pre-thrust template and assess that template's capacity to control subsequent lateral thrust geometries on a variety of scales during allochthon formation within two contrasting fold-thrust belts, the linear Moine Thrust Belt and the oroclinal Cantabrian Thrust Belt.

Within the Kinlochewe region of the Moine Thrust Belt, a distinct compartmentalisation is identified across the Loch Maree Fault (LMF). A thrust dominated region of overturned Torridonian / Lewisian, overlying a right-way-up Cambrian succession can be clearly identified on the northern wall of the LMF, compared to a fold-and-thrust dominated section on the southern wall. Compartmentalisation is suggested to be a response to a step in basement that generated a transport-parallel lateral ramp or sidewall during thrusting. A series of potential cross-strike discontinuities / transverse zones are identified within the Cantabrian Thrust Belt. Structural disparities are suggested to have developed as a result of along-strike variations in stratigraphical thickness and regional transport during a multiphase oroclinal development.

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I would firstly like to thank my supervisors Prof. Graham Williams, Dr Stuart Clarke and Dr Graham Leslie for giving me the opportunity to undertake this research within the Moine, Cantabrian and Appalachian fold-thrust belts and for the support I have received during the write-up of the project. I would also like to thank Keele University and the British University Funding Initiative (BUFI) for funding this research. Further thanks are also reserved for the American Association of Petroleum Geologists (AAPG) for funding research within the Appalachians Thrust Belt, Alabama, USA, through the Raymond D. Woods Memorial Grant.

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I would finally like to dedicate this work to my Mum, who for the whole of my life has tirelessly provided me with love, care and a shoulder to either lean or cry on. This PhD is dedicated to you from a very thankful son.

'TURRIS FORTIS MIHI DEUS'

(God is my Tower and Strength)

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Chapter One:

Thesis Introduction and Organisation

This first chapter introduces the rationale behind this research into the identification and analysis of cross-strike discontinuities and kinematic linkages within the Moine and Cantabrian thrust belts. Aims and objectives of the research are stated, whilst a brief overview of the study areas under investigation is introduced. A summary of the structure of this thesis is also presented.

1.1. Introduction and Research Rationale

Abrupt lateral changes in thrust geometry occur in many mountain-building fold-thrust belts globally with profound architectural complexities segmenting the orogenic front (e.g., Harris & Milici, 1977; Mitra, 1988; Elliott & Johnson, 1980; Butler, 1982; Pérez-Estaún *et al.,* 1988; Rodgers, 1990; Brown *et al.,* 1997; Fermor, 1999). Whilst many works have dealt with palinspastic reconstructions and transport-direction-parallel balanced cross-sections, far fewer have focused on demonstrating a full three-dimensional architecture, or examine how these lateral variations in thrust architecture can be linked via so-called ‘cross-strike discontinuities’ (CSDs) or ‘transverse zones’ that demarcate different segments of the thrust belt (e.g., Drahovzal & Thomas, 1976; Thomas, 1990; Schönborn, 1990; 1992; Paulsen & Marshak, 1997; 1998; Kley *et al.,* 1999; Mouthereau *et al.,* 2002; Thomas & Bayona, 2002; Bayona *et al.,* 2003; Brewer, 2004; Yassaghi & Madanipour, 2008; Krabbendam & Leslie, 2010; Leslie *et al.,* 2010; 2012; Turner *et al.,* 2010; Aschoff *et al.,* 2011).

This relative paucity in research is, in part, a consequence of the difficulty in obtaining rigorous constraint upon the three-dimensional pre-thrust template geological model (e.g., Hinsch *et al.,* 2002; Gorney *et al.,* 2007). In many cases the causative structures for lateral changes are often concealed, either by distal parts of the thrust belt or by the foreland basin, and as such are not fully studied (Krabbendam & Leslie, 2010). However, when identified through deductions from structural architecture, systematic alignments of lateral cross-strike discontinuity structures within transverse zones have been suggested to be related to:

- Kinematic responses to irregularities generated across pre-existing, sometimes re-activated, sub-décollement basement faults,
- Contrasts in pre-thrusting deformation of cover strata above basement faults,
- Development of syn-kinematic deformation structures during allochthon formation (i.e., culminations, duplex structures and antiformal stacks),
- Along-strike variations in mechanical stratigraphy and lithofacies in the deforming sedimentary wedge (Harris, 1970; Wheeler, 1980; Woodward, 1987a; Kulik & Schmidt, 1988; Wiltschko & Eastman, 1988; Hatcher *et al.,* 1989; Thomas, 1990; Álvarez-Marrón, 1995; Pérez-Estaún *et al.,* 1997; Kollmeier *et al.,* 2000; Thomas & Bayona, 2002).

Cross-strike discontinuities / transverse zones therefore represent important syn-kinematic components of thrust-belt evolution. Identifications and analyses of cross-strike discontinuities / transverse zones permit understanding of how pre- and / or syn-kinematic structures and stratigraphical variations affect the syn-kinematic plan of the fold-thrust belt as a whole, as well as, identifying potential pre-thrust weaknesses within active fault systems (e.g., earthquake-prone areas, such as the L'Aquila region; Mantovani *et al.,* 2012). Furthermore, cross-strike discontinuity identifications provide important information for hydrocarbon exploration within potentially complex orogenic exploration settings (e.g., hydrocarbon traps and migration pathways; Bégin & Spratt, 2002).

This research provides the first detailed three-dimensional study of the geometrical architecture of, and linkages across, the Loch Maree Transverse Zone (LMTZ) to determine how thrust units and thrusts link together and relate to each other, and what these linkages mean in terms of lateral changes. A regional-scale identification and analysis of potential cross-strike discontinuities / transverse zones is implemented within the Cantabrian Thrust Belt. A series of potential cross-strike discontinuities / transverse zones are identified, particularly within the south-western hinge of the Cantabrian Thrust Belt, west of the town of San Emiliano. Furthermore, this research identifies the kinematic development of the Loch Maree Transverse Zone (LMTZ) and the development of potential Cantabrian transverse zones. The role the pre-thrust template and regional transport has on the nucleation of transverse cross-strike discontinuities within the study areas is discussed. This research and new methodologies developed enable direct benefits to further research within analogous global fold-thrust belt settings for the identification of potential cross-strike discontinuities / transverse zones whilst also providing detailed information for the development of orogenic systems within the Northwest Highlands and the Cantabrian region of northern Spain.

1.2. Research Aims and Objectives

The general overall aims of this research are to determine the:

- *detailed three-dimensional architecture of, and linkages across, cross-strike discontinuities / transverse zones;*

- *role of thrust translation (i.e., regional transport), in relation to potential pre-existing transverse structures;*
- *effect and / or control the pre-thrust template exerts upon cross-strike discontinuity / transverse zone formation.*

To achieve these aims, specific objectives of the research include the:

- Development of a new thrust ramp identification framework incorporating fault network analyses and stratigraphical separation diagrams to determine regional and localised spatial distributions of transversal structures.
- Acquisition and utilisation of a spectrum of detailed thrust architectural and geometrical observations, construction of a suite of high resolution transport-parallel and transport-lateral cross-sections to identify how thrust units and thrusts link together and relate to each other, and what these linkages mean in terms of lateral changes (i.e., gradational versus abrupt variations).
- Collection and analysis of kinematic data sets for the determination of thrust translation in respect to orientations of pre-existing transverse structures and to determine how these transverse structures evolve within transverse zone developments.
- Assessments of the likely controls on the spatial and temporal evolution of transverse zones to determine what types of pre-existing structures are important (i.e., pre-, syn-, and / or post-depositional), how critical is the wavelength and / or amplitude of potential steps within the pre-thrust template, and how they affect and / or control the thrust system as a whole.

1.3. Location of Study Areas

Two study areas have been selected within well-understood and comprehensively mapped thrust belts, to demonstrate the application of new thrust ramp identification techniques developed within this research. These are implemented to identify and analyse cross-strike discontinuities / transverse zones. The two case study areas are located within the:

- Northern Achnashellach Culmination, Kinlochewe region along the Loch Maree Fault, Moine Thrust Belt, Northwest Highlands, Scotland (Figure 1.1a).
- Somiedo-Correcillas Unit, Cantabrian Thrust Belt (Cantabria-Asturian Arc), northern Spain, with particular focus within the San Emiliano region (Figure 1.1b).

New identification techniques are tested prior to application within the Moine and Cantabrian thrust belts. A small-scale test site was chosen within the Bessemer Transverse Zone, southern Appalachian Thrust Belt, Alabama, USA (Figure 1.1c).

Study areas have been carefully chosen to identify and interpret individual cross-strike discontinuities / transverse zones within two varying geological settings, a classic linear fold-thrust-belt geological setting, and a less orthodox oroclinal fold-thrust belt geological setting within which no previous transverse zone identifications have been interpreted, but where structural style changes have been observed. Detailed discussion on each of the study areas, the identification and analysis of cross-strike discontinuities / transverse zones, and the role of the pre-thrust template and regional transport direction is given in chapters four, five and six. The following sub-sections serves as a brief introduction to the study areas.

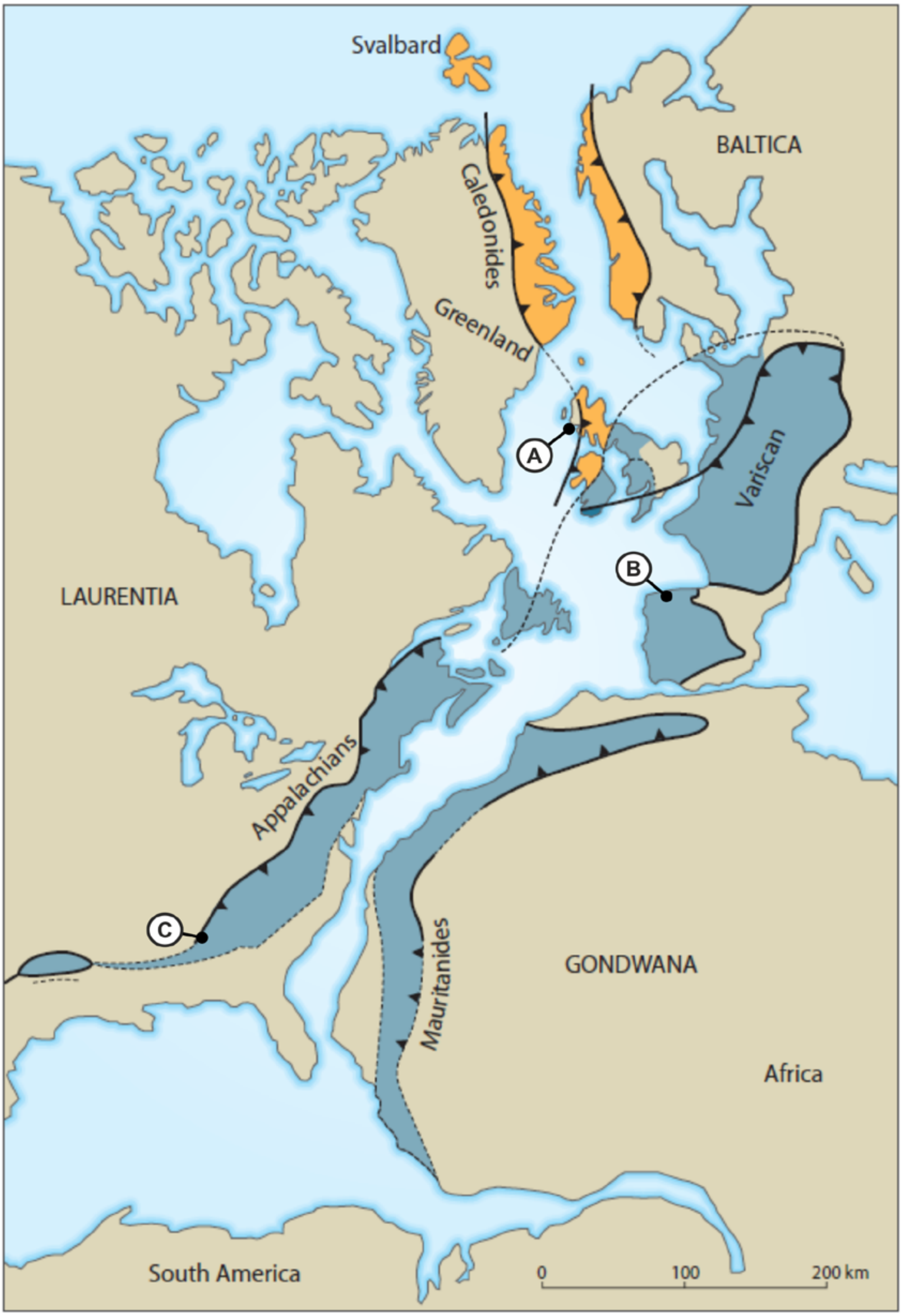


Figure 1.1: Map of the Palaeozoic highlighting selected study and test area fold-thrust belts around the North Atlantic Ocean and the continents shown in their relative position ca. 300 Ma prior to sea floor spreading created the present Atlantic Ocean. The Caledonian fold-thust belt in the north, shown in orange, was formed by continental collision between Laurentia and Baltica in the Silurian. This collision produced the Moine Thrust Zone, Northwest Highlands, Scotland **(A)**. Other fold-thrust belts depicted reflect the continental collisions of Laurentia and related areas with various micro-continents and Africa, a sequence of tectonic events that lasted into the Carboniferous producing the Variscan and Appalachian fold-thrust belts. The Cantabrian Thrust Belt (Cantabria-Asturian Arc), northern Spain is identified within the western Variscides **(B)**, whilst a small-scale test case was undertaken to test thrust ramp identification methodologies within the southern Appalachian Thrust Belt, Alabama, USA **(C)**. (Adapted after Henriksen *et al.*, 2008)

1.3.1. *Northern Achnashellach Culmination, Kinlochewe region along the Loch Maree Fault, Moine Thrust Belt, Northwest Highlands, Scotland*

The Achnashellach Culmination comprises a thirty kilometre long, ten kilometre wide, series of imbricate thrusts forming a bulge or culmination within the footwall of the overriding Kinlochewe and Moine thrusts (Figure 1.2a). Up to one kilometre of Torridon Group sediments, together with a further two hundred to two hundred fifty metres of Cambrian strata produce a ramp-on-ramp geometry. The culmination is limited on its flanks by lateral ramps that climb section out of Torridon Group lithologies into Cambrian strata. The northward-climbing lateral ramp coincides with a major Precambrian structure, the Loch Maree Fault. The study area represents a region approximately twelve and a half kilometres by ten kilometres covering the cross-strike disparity identified within the northern and southern walls of this dominant structure, from Beinn Eighe within the southern wall, to the Heights of Kinlochewe within the northern wall.

1.3.2. Somiedo-Correcillas Unit, Cantabria-Asturian Arc, northern Spain, with particular focus within the San Emiliano region

Within the south-western Variscides, a prominent bend called the Ibero-Armorican or Cantabria-Asturian Arc is identified demonstrating nearly 180° curvature within the Iberian Massif. The Cantabrian Zone (i.e., Cantabrian Thrust Belt) resides within the core of this structure, characterised by thin-skinned tectonics with a transport-direction indicating foreland-directed concavity with inward-facing structures. The Cantabrian Zone is subdivided into several tectonic units including the Somiedo-Correcillas Unit, where this research is specifically focused (Figure 1.2b). Research undertaken over the scale of the Cantabria-Asturian Arc within the Somiedo-Correcillas Unit identifies a series of potential cross-strike discontinuities / transverse zones. Particular focus is attributed to structural disparities identified within the San Emiliano region (Figure 1.2b).

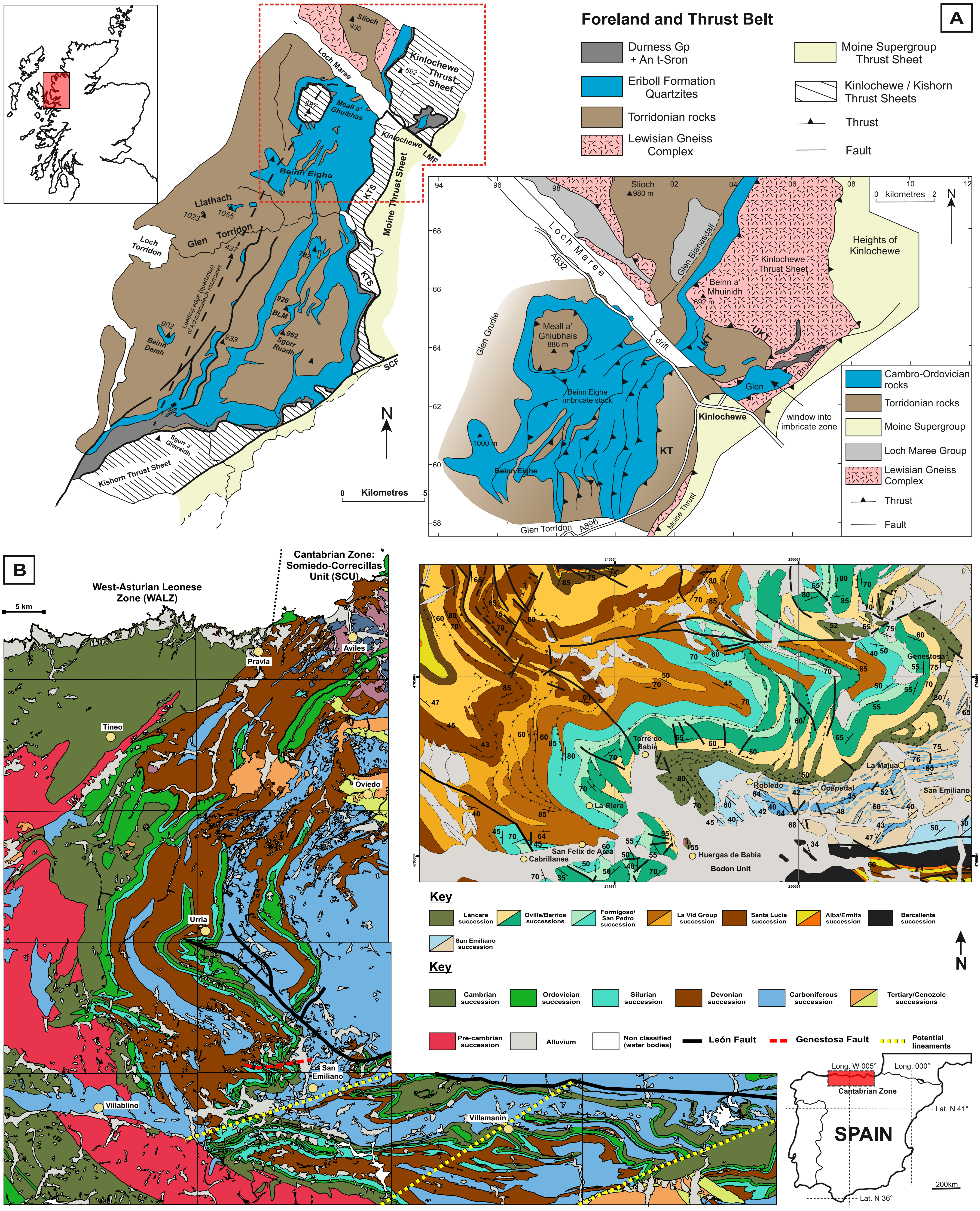


Figure 1.2: **(A)** Northern Achnashellach Culmination study area, Kinlochewe region along the Loch Maree Fault, Northwest Highlands, Scotland (Adapted after Peach *et al.*, 1907; Butler *et al.*, 2007). **(B)** Identification of potential cross-strike discontinuities / transverse zones within the Somiedo-Correcillas Unit, Cantabria-Asturian Arc, northern Spain. Particular focus is assigned to structures within the San Emiliano region along structures such as the Genestosa Fault and structures within the Villamanin region. Geological maps simplified from MAGNA (1:50;000-scale) map series of the Instituto Tecnológico GeoMinero de España (e.g., Lobato *et al.*, 1984, Matas & Rodríguez Fernández, 1984; Alonso, 1989; Alonso *et al.*, 1989; 1991; Álvarez-Marrón *et al.*, 1989; Bastida & Gutiérrez, 1989; Marquinez, 1989; Suárez Rodríguez *et al.*, 1990.

1.4. Thesis Structure

Table 1.1 summarises the structure of this thesis with a brief description of each chapter and the data utilised within.

Summary of Thesis Organisation		
Chapter	**Title**	**Description**
1	Thesis Introduction and Organisation	Rationale, aims and objectives for this research outlined; brief geological setting provided for areas under investigation. Thesis outline provided.
2	Cross-strike Discontinuities / Transverse Zones in Thrust Belts: Research History	Presents a discussion on cross-strike discontinuity / transverse zone research development over the last fifty years. Potential pre-thrust controls and subsequent syn-kinematic map-trace phenomena respective of thrust translation are discussed.
3	Architectural analysis of Transverse Zones: new identification and classification methodologies	Cross-strike discontinuity / transverse zone identification techniques reviewed. New colour coding methodology discussed and tested within the Bessemer Transverse Zone, southern Appalachians prior to utilisation within the Moine and Cantabrian thrust belts.
4	Kinematic partition within the Moine Thrust Belt: Loch Maree Transverse Zone (LMTZ) southern wall	Geological setting and previous research within study area reviewed. Detailed fault network analysis of the Achnashellach Culmination presented. Overview of the Loch Maree Transverse Zone (LMTZ) provided, followed by detailed observations and cross-sectional analyses within the LMTZ southern wall (i.e., the Beinn Eighe and Meall a' Ghiubhais sectors). Three-dimensional cross-strike relationships identified using transport-parallel cross-sections. Observations placed in context with LMTZ northern wall within Chapter 5.
5	Kinematic partition within the Moine Thrust Belt: Loch Maree Transverse Zone (LMTZ) northern wall	Detailed observations, fault network and cross-sectional analyses within the LMTZ northern wall (i.e., the Heights of Kinlochewe sector) are presented. Three-dimensional cross-strike relationships identified using transport-parallel cross-sections. Observations identified within the LMTZ southern wall within Chapter 4 are placed in context for the development of cross-strike linkages. Development of the LMTZ is discussed whilst the role of the pre-thrust template and transport direction are analysed.
6	Identification of potential Transverse Zones in Thrust Belts: Somiedo-Correcillas Unit, Cantabrian Thrust Belt, northern Spain	Potential cross-strike discontinuities / transverse zones are identified within the oroclinal Ibero-Armorican Arc (Cantabrian Mountains), northern Spain using regional (fold-thrust belt wide) analyses of thrust ramps and structural styles within new fault network analyses. Series of potential cross-strike discontinuities / transverse zones identified. Small-scale focused research along key frontal and transverse structures identified, particularly within the San Emiliano and Villamanín regions.
7	Discussion and Wider context within cross-strike discontinuity / transverse zone research	Findings identified within this research are placed within the context of global research into cross-strike discontinuities / transverse zones. Assessments of the likely controls on the spatial and temporal evolution of transverse zones to determine what types of pre-existing structures are important (i.e., pre-, syn-, and/or post-depositional), how critical is the wavelength and / or amplitude of potential steps within the pre-thrust template, and how they affect and / or control the thrust system as a whole. The role of transport is also discussed.
8	Conclusions and Future Work	Summarises the results of this research and implications for future study.

Table 1.1: Summary of thesis organisation

Chapter Two:

Cross-strike Discontinuities / Transverse Zones in Thrust Belts:

Research History

To determine three-dimensional architectures of, and linkages across, cross-strike discontinuities / transverse zones; the role of thrust translation in relation to pre-existing transverse structures; and the effect / control the pre-thrust template exerts upon cross-strike discontinuity / transverse zone formation, a review of pertinent cross-strike discontinuity / transverse zone research development and identification criteria over the last fifty years is required. Emphasis is placed on critical observations of key cross-strike discontinuity phenomena, whilst suggested controls for their development within transverse zones are discussed.

2.1. Cross-strike discontinuities / transverse zones within thrust belts: A review

Foreland thrust systems within orogenic belts are composed of a series of sub-parallel thrust faults and related folds, bounded by a three-dimensional system of interconnected fault surfaces detached at a basal décollement (i.e., imbricate thrust sheets; Boyer & Elliott, 1982). Imbricate thrust sheets are thickened as they are translated towards the continental craton, defining a regional structural grain (i.e., an allochthon; Thomas, 2007). Thrust sheets incorporate:

- thrust detachment flats that run parallel to stratigraphical bedding at the time of thrust translation,
- strike-parallel frontal thrust ramps that cut obliquely up-stratigraphical section in the direction of translation,

- lateral and / or oblique thrust ramps that are the strike-perpendicular and strike-oblique equivalents, respectively, of frontal ramps)
- transverse faults (Rich, 1934; Dahlstrom, 1970; Price, 1981; Boyer & Elliott, 1982; Butler, 1982a; Davis *et al*., 1983; Suppe, 1983; Thomas, 1990; 2007; Apotria *et al*., 1992; Thomas & Bayona, 2002)

Structural profiles of frontal ramps, and their associated fault-bend folds, persist along-strike for considerable distances parallel to thrust belt trends. However, these structures have relatively abrupt, rather than gradual, along-strike terminations in thrust architecture creating along-strike structural discontinuity phenomena (Wilson & Stearns, 1958; Laubscher, 1981; 1985; Dahlstrom, 1969; Price, 1981; Thomas, 1985; 1990). At frontal ramp intersections, fault displacement is transferred across strike to another frontal ramp. Fault displacement is accommodated via cross-strike linkages which are parallel with, or oblique to, the thrust belt transport direction (Wilson & Stearns, 1958; Dahlstrom, 1970; Harris, 1970; Laubscher, 1981; O'Keefe & Stearns, 1982; Mitra, 1988; Thomas, 1990; 2001; Thomas & Bayona, 2002; Brewer, 2004). Principal cross-strike linkages include: lateral and / or oblique ramps, displacement-transfer zones and transverse faults (Figure 2.1; Thomas, 1990). Syn-kinematic phenomena representing map-view deformations associated with cross-strike linkages are also documented including; duplexes, antiformal stacks, geological windows, culmination developments and deflected folds and thrusts associated with along-strike buttressing, transpression, transtension and vertical-axial rotations of thrust sheets.

Locations of cross-strike linkages and cross-strike discontinuity phenomena within stratigraphical successions are commonly controlled by contrasts in mechanical properties

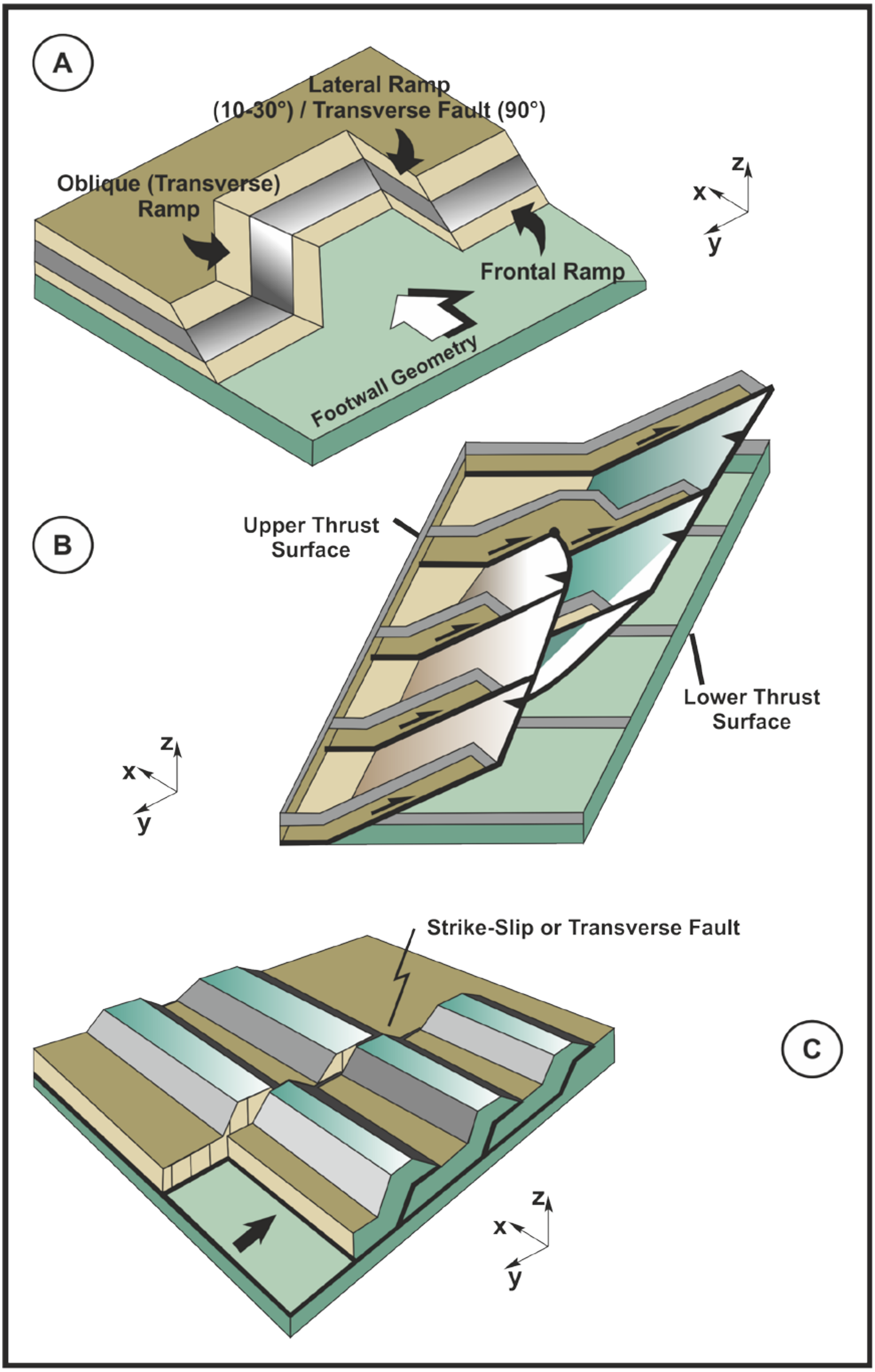


Figure 2.1: Cross-strike linkages / lateral connectors within transverse zones. **(A)** Lateral ramp (typically dipping 10-30°) / transverse fault (90° / near vertical) shown in relation to frontal and oblique thrust ramps (Adapted after Apotria, 1992) **(B)** Example of a simple (lap-joint / en-echelon type) displacement-transfer zone (Adapted after McClay, 1992) **(C)** Example of a transverse / strike-slip fault (Adapted after McClay, 1992)

of strata undergoing deformation, by sub-décollement basement structures which modify stress fields responsible for allochthon formation, or by combinations of the two (Woodward, 1988; Kulik & Schmidt, 1988; Wiltschko & Eastman, 1988; Woodward *et al*., 1988; Hatcher *et al*., 1989). Cross-strike linkages and syn-kinematic cross-strike discontinuity phenomena may therefore be randomly distributed within the allochthon. However, many cross-strike linkages and phenomena are aligned into kilometres-wide zones termed cross-strike structural discontinuities (CSDs), representing the surface expression of transverse zones which encompass the various cross-strike linkages and discontinuity phenomena (Thomas, 1990; Berger, 2001). It follows that transverse zones are the three-dimensional extension of CSDs at depth, terminating at the allochthon base (Thomas, 1990; Brewer, 2004).

2.1.1. Lineaments to cross-strike discontinuities and transverse zones

Fifty years of research has identified transverse zones as lineaments, lateral ramps and cross-strike discontinuities (CSDs) from worldwide fold-thrust belt field investigations (Appendix A). Important examples include the:

- <u>Appalachians</u> (e.g., Rodgers, 1963; 1970; Gwinn, 1964; Thomas & Drahovzal, 1974; Drahovzal & Thomas, 1976; Wheeler *et al*., 1979; Wheeler & Dixon, 1980; Wheeler, 1980; 1986; Lavin *et al*., 1982; Coleman, 1988b; Mitra, 1988; Hatcher, 1989; Thomas, 1990; 2007; Keller & Hatcher, 1999; Thomas & Bayona, 2002; 2005; Bayona *et al*., 2003; Brewer, 2004; Tull & Holm, 2005; Cook & Thomas, 2009; Cook, 2010);

- <u>Rocky Mountains, Utah</u> (e.g., DeCelles *et al*., 1995; Paulsen & Marshak, 1997; 1998; Kwon & Mitra, 2006; Aschoff *et al*., 2011);

- Canadian Rockies (e.g., McMannis, 1963; Price, 1967; 1981; 2001; Price *et al*., 1972; Kanasewich *et al*., 1969; Schmidt, 1976; Benvenuto & Price, 1979; Meyers, 1980; 1981; Thompson, 1981; Schmidt & O'Neill, 1982; Schmidt *et al*., 1988; Fermor, 1999; Bégin & Spratt, 2002);

- Andes (e.g., Kley *et al*., 1999; Hinsch *et al*., 2002; Mon *et al*., 2005; Giambiagi *et al*., 2008);

- Southern Alps (e.g., Laubscher, 1981; 1985; Schönborn, 1990; 1992; Bonini *et al*., 2010);

- Himalayan foreland fold-thrust belt, Pakistan (e.g., McDougall & Khan, 1990);

- Pyrenees (e.g., Soto *et al*., 2002);

- Uralides (e.g., Kamaletdinov, 1975; Brown *et al*., 1997; Pérez-Estaún *et al*., 1997; Giese *et al*., 1999);

- Apennines (e.g., Castellarin *et al*., 1982; Bigi *et al*., 1995; Alberti *et al*., 1996; Tavarnelli, 1996; Muttoni *et al*., 1998; Scisciani *et al*., 2002; Tavarnelli *et al*., 2001; Tozer *et al*., 2002; Butler *et al*., 2004; 2006; Alcicek & ten Veen, 2008; Satolli & Calamita, 2008; Pizzi & Galadini, 2009; Scisciani, 2009; Calamita *et al*., 2011; Di Domenica *et al*., 2012a; 2012b; Mantovani *et al*., 2012; Pace *et al*., 2012a)

- Zagros fold-thrust Belt (e.g., Burberry *et al*., 2011; Motamedi *et al*., 2012)

- Moine Thrust Zone, NW Highlands, Scotland (e.g., Krabbendam & Leslie, 2004, 2010; Leslie *et al*., 2010; 2012; 2013)

- Keping Shan Thrust Belt, China and the Taiwan fold-thrust belt (e.g., Turner *et al*., 2010 and Mouthereau *et al*., 2002 respectively)

Primary investigations of regional lineaments, along-strike structural variations and various thrust-belt offsets began within the northern Appalachians and Canadian Rockies during the 1960s and 1970s. Research focused on the modes of occurrence of abrupt lateral variation phenomena, rather than on causes and controls of these thrust-belt features. Initial observations by Rich (1934) and Rodgers (1963) within the northern Appalachian Thrust Belt concluded that thrust-belt lineaments marked diffuse boundaries between blocks partly decoupled during thrusting and deformed independently, creating incipient tear faults or strike-slip fault-lineaments. Kowalik (1975) in his analysis of Gwinn-type lineaments (e.g., Kowalik & Gold, 1974 *in* Gwinn, 1964), supplemented this by suggesting that decoupling occurred along pre-thrust zones of weakness within thrust sheets and fracture zones propagated upward from basement faults underlying thrusts. Trumbo (1976) supplemented this by hypothesising that pre-thrusting weaknesses in thrust sheets were formed at vertically stacked facies changes.

Growing global interest in the location, causes and controls of along-strike variations within fold-thrust belts during the 1960s and 1970s highlighted the importance of these structures within all thrust belts, and that they were simply not just random occurrences. Subsequently, this class of thrust belt structure were first termed 'cross-strike structural discontinuities' (CSDs) by Drahovzal & Thomas (1976), in an abstract on regional lineaments cutting across structural strike in the Alleghanian Thrust Belt, Alabama, USA.

Wheeler *et al*., (1979) were the first, in numerous thrust belts, to summarise the sizes and characteristics of cross-strike discontinuities, or groups of cross-strike discontinuities, to explore their potential to yield hydrocarbon-bearing deposits. Wheeler's findings introduced the concept of cross-strike discontinuities as fundamental parts of the evolution of several thrust belts including the Appalachians, the Canadian Rockies and the Chilean

Andes. Wheeler *et al*., (1979) suggested that cross-strike discontinuity spatial distributions vary in depth and width and may typically be located within highly fractured areas of the allochthon where sub-décollement basement may or may not be involved within formation.

Following further study, Wheeler (1980) hypothesised that within the Appalachians, on average, transverse zones were typically three and a half kilometres wide, reaching a maximum width of roughly thirty kilometres, (e.g., Laubscher, 1985), at least four kilometres deep and at least seventy kilometres long, with an offset of about twenty five kilometres between adjacent transverse zones, although global studies since indicate transverse zone formation to be scale independent. Wheeler (1980) concluded that cross-strike discontinuity (CSD) geometries might be influenced by cratonic structures activated, or reactivated, under advancing thrust sheets. Wheeler (1980) also highlighted key identification criteria for CSDs within global studies (Table 2.1 / Appendix B).

Thomas (1990) was the first to discuss the finer-scale anatomy of transverse zones, proposing that transverse zones were composed of 'lateral connectors' (later redefined as cross-strike linkages in Thomas & Bayona, 2002), a variety of which may be aligned orthogonal to regional strike forming thrust-belt discontinuities. Thomas (1990) defined the characteristics of three principal types of cross-strike linkage: (1) lateral ramps, (2) displacement transfer zones, and (3) transverse faults (Figure 2.1). Cross-strike extents of each cross-strike linkage are limited by the leading and trailing frontal ramps which bind single thrust sheets within a thrust system (Dahlstrom, 1970; Harris, 1970; Mitra, 1988). Combinations of structural and stratigraphical variations, both internal and external to the allochthon including, sub-décollement basement faults, pre-thrusting deformation of cover strata above basement faults, and / or along-strike variations in mechanical stratigraphy were identified by Thomas (1990) as controlling cross-strike linkage alignments within transverse zones.

Transverse zone identification criteria
1. Along-strike terminations / curves / offsets of detached folds, longitudinal thrust faults and / or ramp anticlines…
2. Presence of a small fold or fault that records larger movements…
3. High joint intensity within a section, a large size, close spacing or combinations of the two…
4. Development of intense cleavage…
5. Transverse faults, particularly if movement occurred at more than one time, in more than one direction, or a combination of both (sub-décollement basement faults / basement-rooted faults in cover strata…
6. Anomalous changes in contours of smoothed values of dip or strike of particular beds…
7. Changes in orientation of structural grain…
8. Abrupt changes in depth to magnetic basement / disruptions in magnetic or gravity anomalies, particularly with terrane corrections…
9. Mineralisation: Usually abundant or indicative of deeply penetrating fracture systems…
10. Earthquake epicentres / volcanic centres and intrusions…
11. Course changes of major streams / deflections of drainage systems / water and / or wind gaps…
12. Long Landsat photolineaments / Unusually dense air photo lineaments…
13. Facies and thickness changes of stratigraphical units…
14. Blocky shapes on isopach maps, including abrupt thickness changes across straight lines…
15. Springs: unusual temperatures, chemistries and / or yields…
16. Gas or oil seeps / High or low yields of water or gas wells…
17. Recess / salient production (Irregularly shaped, rifted continental margins)…
18. Localised thrust-sheet rotations (vertical-axis rotations)…
19. Along-strike variations in structural style (e.g., thick- / thin-skinned deformation) / lateral shortening / buttressing effects (e.g., duplex / antiformal stack formation)…
20. Along-strike variations in degree of reactivation or pre-existing structures (e.g., inversion)…
21. Along-strike changes in flexural subsidence (differential loading around transverse zones)…

Table 2.1: Transverse zone identification criteria used in previous global research (Adapted after Wheeler, 1980)

2.1.1.1. Lateral ramps

Term 'lateral ramp' was first used by Boyer & Elliott (1982), Butler (1982a), and Hossack (1983) to describe a tectonic ramp parallel to the transport direction of regional thrust sheets. That definition was expanded by Thomas (1990), who described lateral ramps as a transverse fault structure which cuts through the beds between the lower- and upper-level detachment horizons, accommodates an along-strike change of stratigraphical level of décollement, and connects the orthogonally offset ends of two separate frontal ramp segments (Figure 2.2a). The transverse fault either forms part of the upper surface of autochthonous rocks or forms the lateral termination of a thrust sheet (if the frontal ramps are splays from a through-going lower-level detachment, Figure 2.2b) (e.g., Rich, 1934; Butler, 1982a; Thomas, 1990; Apotria *et al.*, 1992).

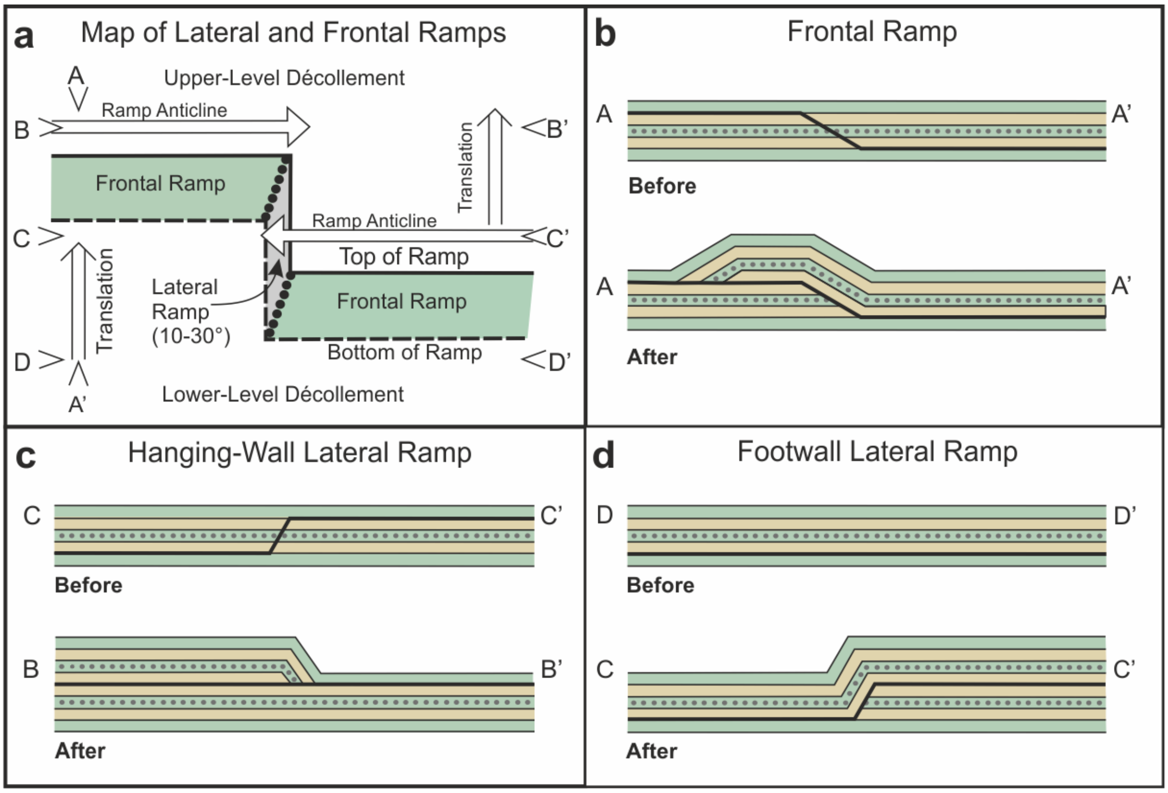


Figure 2.2: Idealised map and cross-sections of lateral and frontal ramps **(a)** Map shows trace of thrust ramps on footwall (black lines) and locations of ramp anticlines in hanging-wall (wide arrow heads represent plunge) **(b-d)**. Cross-sections illustrate pre-thrusting position of fault trace (upper diagram) and hanging-wall post-thrusting configurations (lower diagram) (Thomas, 1990)

Strictly defined, lateral ramps strike 90° to the connected frontal ramp, with lateral ramp dips commonly between 10°and 30°. It must be noted that if the lateral structure is vertical then it becomes a thrust transport-parallel tear or strike-slip (transverse) fault and therefore should not be termed a lateral ramp (Figure 2.1, 2.2; McClay, 1992).

Two types of lateral ramps, the hanging-wall and the footwall, are clearly defined within transverse zone research (Woodward *et al*., 1988; Kulik & Schmidt, 1988; Hatcher *et al*., 1989). In a hanging-wall lateral ramp, hanging-wall rocks are thrust onto the upper-level detachment, forward of the intersection between the leading frontal ramp and the backward connecting lateral ramp (Figure 2.2c; Thomas, 1990). Allochthonous beds from the hanging-wall cut-off of the lateral ramp are inverted to form the plunging end of a ramp anticline, while the thrust fault in the hanging-wall lateral ramp cuts through the hanging-wall stratigraphical succession (Figure 2.2c; Thomas, 1990; Brewer, 2004; Cook & Thomas, 2009). Fault surface elevation is constant within the thrust fault cutting bedding along-strike (Thomas, 1990).

In a footwall lateral ramp, hanging-wall rocks are transported onto the upper-detachment, forward of the intersection between the trailing frontal ramp and the forward connecting lateral ramp (Figure 2.2d). Hanging-wall rocks form a plunging fold within the same axial trend as the lateral ramp strike which drapes over the lateral ramp footwall cut-off (Cook & Thomas, 2009). The thrust fault in the footwall lateral ramp remains within the stratigraphical unit at the base of the hanging-wall succession (cross-section D-D’, Figure 2.2d; Thomas, 1990; Thomas & Bayona, 2002; Brewer, 2004). Bedding at the allochthon base is cut by the transverse fault, but plunging folds within both the footwall and hanging-wall lateral ramps continue upward to the surface. No transverse fault is required within the allochthon to connect the offset ends of the variably plunging folds (Thomas, 1990).

2.1.1.2. Displacement Transfer Zone

Dahlstrom (1969) and Thomas (1990) discussed potential problems in comparing shortening along individual thrust faults versus shortening in entire thrust belts identifying that shortening percentages are substantially greater in local structures than overall shortening amounts for the thrust belt as a whole. Dahlstrom (1969) stated that since the whole thrust belt does not change as rapidly as its component parts, it follows that there must be some compensating mechanism whereby displacement is transferred from one structure to another.

Dahlstrom (1969) introduced the concept of displacement transfer zones in thrust belts accommodated via cross-strike links transverse or oblique to allochthon strike through a 'lap-joint fault'; a fault experiencing along-strike decrease in displacement being replaced by an en-echelon fault experiencing along-strike displacement increase (Wilson & Stearns, 1958; Dahlstrom, 1970; Harris, 1970; Laubscher, 1981; O'Keefe & Stearns, 1982; Mitra, 1988; Thomas, 1990; Thomas & Bayona 2001; 2002; Brewer, 2004). Translation decreases in opposite directions, whilst net translation on the two frontal ramps is approximately constant along-strike. Both en-echelon faults are required to be rooted in a common detachment surface, along which transfer occurs (Figure 2.3). No transverse fault is required within displacement-transfer zones (Thomas, 1990).

Displacement-transfer zones are commonly associated with the hanging-wall response to oblique ramps within thrust systems creating more gradual and continuous deformation and structural transition patterns along-strike (e.g., Gardener & Spang, 1973; Pfiffner, 1981; Goldburg, 1984; Mitra, 1988; Kwon & Mitra, 2006). Concepts of tear-fault displacement transfer zones are well documented in geological literature, whilst displacement transfer zones not utilising tear faults are also common (e.g., Wilson & Stearns, 1958; Price & Mountjoy, 1970; Laubscher, 1981).

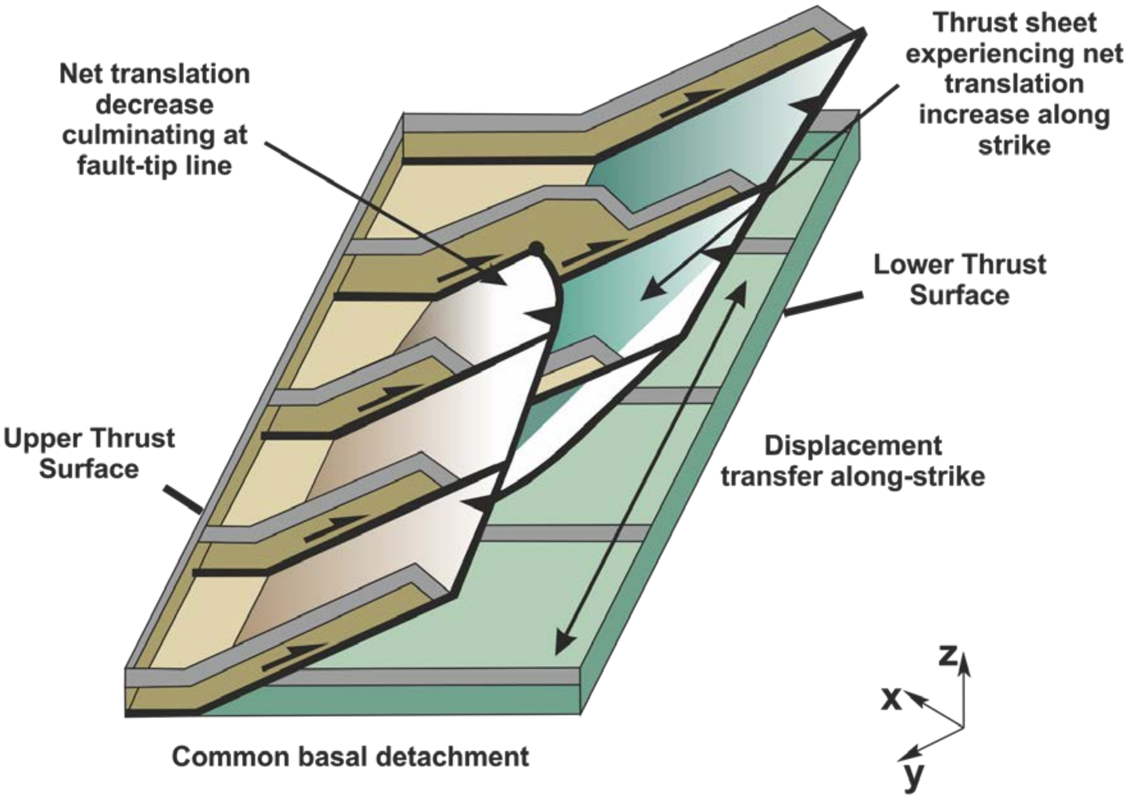


Figure 2.3: Simple (lap-joint / en-echelon type) displacement-transfer zone (Adapted after McClay, 1992). Upper and lower thrust sheets are linked down-dip via a common detachment surface, whilst net displacement is 'transferred' from one thrust sheet along-strike to the next, thus allowing thrust translation to persist along-strike.

2.1.1.3. <u>Lateral ramps vs. Displacement transfer zones in nature</u>

Within nature, differences between lateral ramps and displacement-transfer zones are often hard to determine. Similar geometrical relationships, in terms of relative position of fault trace with respect to the stratigraphical section in map view, can also be attained in other ways (e.g., frontal ramp with displacement gradient, Wilkerson *et al.*, 2002; Figure

2.4). In both lateral ramp and displacement-gradient models, ramps connect lower and upper stratigraphical levels of detachment (Bayona *et al*., 2003).

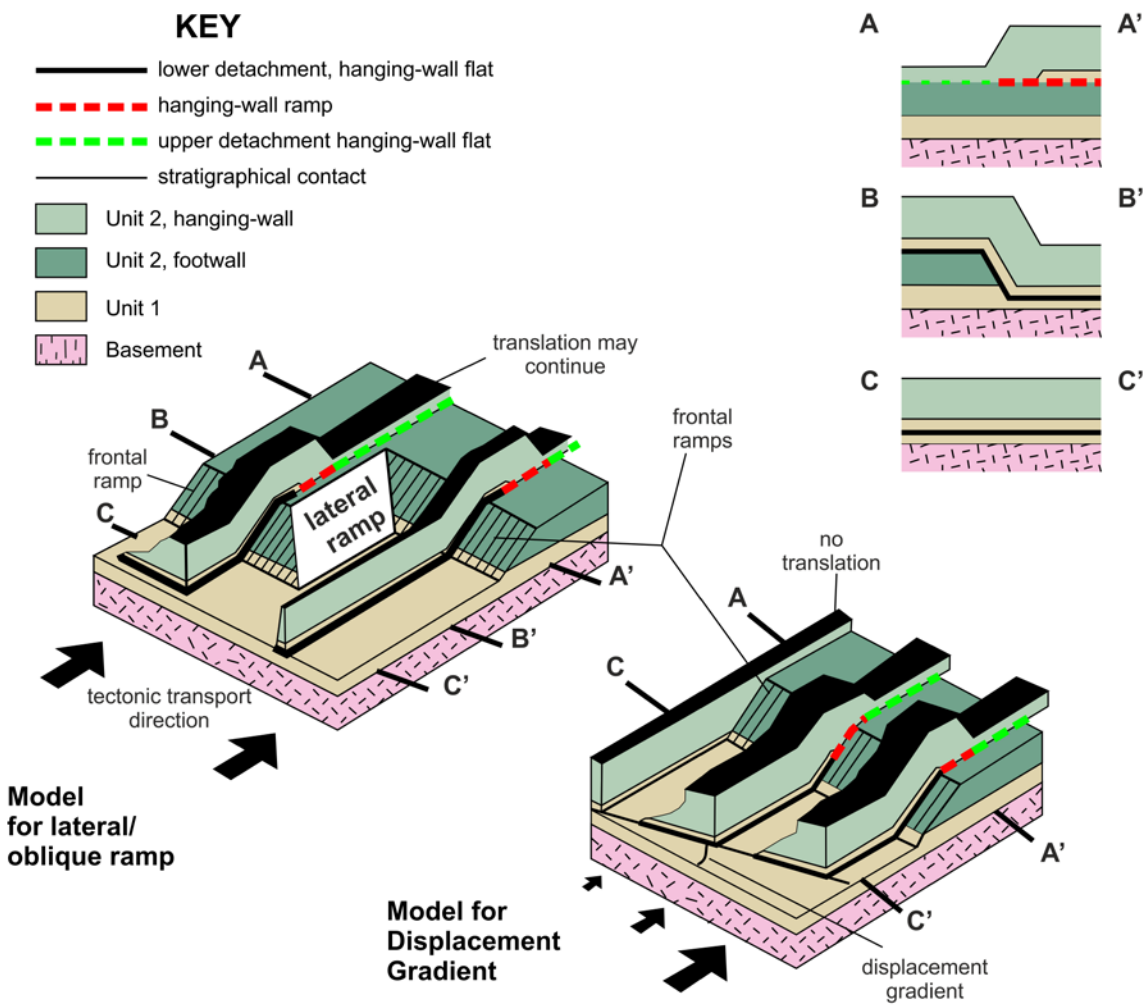


Figure 2.4: Schematic block diagrams and strike-parallel cross-sections, showing two possible mechanism to explain lateral termination and plunging of hanging-wall strata, lateral ramps and displacement gradients. Cross-sections A-A' and C-C' apply to both models, whereas cross-section B-B' only applies for the model of lateral ramps (Adapted after Bayona et al., 2003)

Commonly, combinations of both processes are identified within transverse zones. Kwon & Mitra (2012) highlight this occurrence within observations along the Lemington Canyon Thrust, Provo Salient, Sevier fold-thrust belt, where previous research by Paulsen & Marshak (1998) had identified only lateral ramps creating abrupt along-strike variations. Kwon & Mitra (2012) interpreted a combination of lateral ramps and lateral decreases in slip magnitude along frontal ramps. A further example can be identified within the

Anniston Transverse Zone, where minor differences in thrust translation were absorbed by displacement-transfer zones along-strike between lateral ramps orientated over basement faults (e.g., Apotria, 1995; Allerton, 1998; Wilkerson *et al*., 1991; 2002; Thomas & Bayona, 2002).

2.1.1.4. Transverse Faults

Also known as tear- or compartmental-faults, transverse faults are common in thrust sheets because of the mechanical impossibility of displacing very large volumes of rock as a single unit (Thomas, 1990; Brewer, 2004). Large thrust sheets are commonly broken into smaller structural units bounded by trailing ramps and transverse faults, usually confined to a single thrust sheet, dying out at the regional major décollement surface (Berger, 2001; Figure 2.5). Although a thrust sheet may be broken into smaller structural units, the kinematic history of the smaller units is linked with the translation of the thrust sheet as a whole (Thomas, 1990). Calassou *et al*., (1993) further quantified this within experimental models, identifying key boundary condition changes along individual thrust sheet edges.

Transverse faults also serve as partitions between thrust sheet domains in which a common magnitude of shortening has been achieved in different ways (i.e., a transverse fault separating a fold-dominated domain from another that is fault-dominated, examples of which can be seen within many global thrust-and-fold belts including the Moine and Cantabrian thrust belts; e.g., Kollmeier *et al*., 2000). Strike-slip fault zone interactions have also been identified as causes of along-strike variations in thrust belt curvature (e.g., Cook, 2010). Well documented examples include the St. Mary and Moyie faults, south-western Alberta / south-eastern British Columbia (e.g., Benvenuto & Price, 1979).

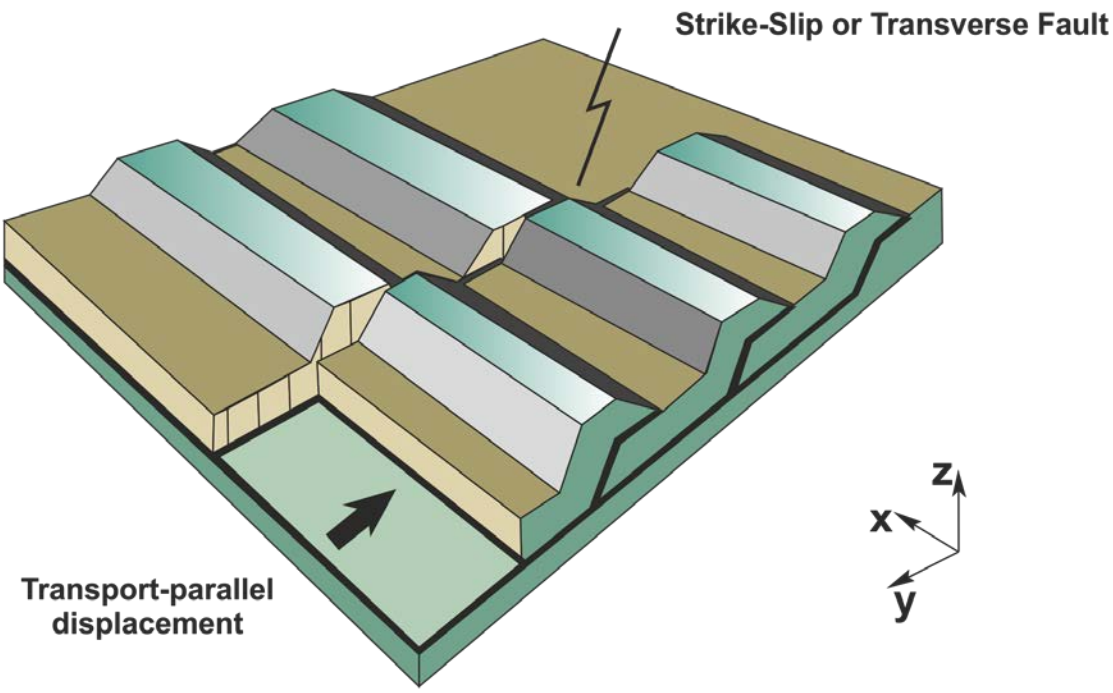


Figure 2.5: Example of a transverse / strike-slip fault. Transverse faults separate two parts of a thrust sheet and / or individual thrust sheets which have experienced differential displacement along-strike within a thrust system. (Adapted after McClay, 1992)

Cross-strike linkages within a single transverse zone commonly exhibit a range of types, scales and senses of apparent offset in map-view, expressed in various manners trending at high angle to regional structural grain, potentially across the entire thrust belt (i.e., cross-strike discontinuity phenomena; Thomas, 1990) including:

- Along-strike terminations of thrust faults and ramp anticlines;
- Curves and offsets in strike along longitudinal thrust faults and associated folds;
- Along-strike changes in dip angle and direction of fold limbs and fold plunges;
- Changes in direction of thrust and fold vergence
- Along-strike changes in stratigraphical levels of detachments and structural styles (Drahovzal *et al*., 1974; Drahovzal & Thomas, 1976; Wheeler, 1978; 1980; Wheeler *et al*., 1979; Thomas, 1985; 1990).

As a result of variations in expression along the trend of a transverse zone, Thomas (1990) interpreted these structures to be distinct from younger transverse normal faults or strike-slip faults that displace thrust-faulted rocks. Cross-strike discontinuities may therefore be regarded as a map-view representation of the three-dimensional geometry of a transverse zone at depth, terminating at the allochthon base (Thomas, 1990; Brewer, 2004).

Since the original classification of cross-strike linkages identified in Thomas (1990), cross-strike discontinuity and transverse zone research has focussed not only on kinematic and geometrical analyses of transverse zones, but also on the fundamental internal and external controls upon cross-strike discontinuity development inherent within the pre-thrust template (e.g. Schönborn, 1992; Pérez-Estaún *et al*., 1997; Paulsen & Marshak, 1997; 1998; Kley *et al*., 1999; Mouthereau *et al*., 2002; Bayona *et al*., 2003; Krabbendam & Leslie, 2004; 2010; Kwon & Mitra, 2006; Leslie *et al*., 2010). Investigations have further developed understanding of sub-décollement controls on pre-thrust stratigraphical deposition and basement architecture discussed in Thomas (1990) through palaeogeographical and palinspastic reconstructions of palaeomargins along well-established transverse zones, such as the Anniston and Bessemer transverse zones, southern Appalachians, USA (e.g. Thomas & Bayona 2002; Brewer, 2004; Tull & Holm, 2005; Cook, 2010).

Recent studies have also focussed on the economic importance of transverse zone research with regard to hydrocarbon exploration strategies, compartmentalisation, fluid migration pathways and hydrocarbon trapping capacities during culmination development within transverse zones in setting such as the:

- Limestone Mountain Culmination, Rocky Mountains, USA (e.g., Bégin & Spratt, 2002);
- Black Warrior Basin, Alabama, USA (e.g., Pashin *et al*., 2010);
- South Provo Salient, Utah, USA (e.g., Aschoff *et al*., 2011);
- Central Alborz Range and Central Fars, Iran (e.g., Yassaghi & Madanipour, 2008; Burberry *et al*., 2011; Motamedi *et al*., 2012);
- Keping Shan Thrust Belt, China (e.g., Turner *et al*., 2010).

Cross-strike discontinuity research and the influence that pre-thrust template inheritance structures play within fold-thrust belt developments have also been used to identify fundamental weaknesses within the allochthon where seismic event epicentres may be focused, most notably within the L'Aquila region, Apennines, Italy (e.g., Mantovani *et al*., 2012). Latest studies have also built on developments in transverse zone studies and digital technologies allowing developments from analogue and geometrical modelling techniques (e.g., Wilkerson *et al*., 1991; Calassou *et al*., 1993; Price 2001; Konstantinovskaya *et al*., 2007) to development of transverse zone digital models (e.g., Bigi *et al*., 2009). Most notable studies include those within the Traligill Transverse Zone, Assynt Culmination, Moine Thrust Zone, Northwest Highlands, Scotland, where detailed strike-parallel and strike-lateral cross-sections have been developed to create fence diagrams. Fence diagrams allow pseudo-three-dimensional properties to be viewed within subsequent three-dimensional models, which can be analysed for academic, industrial and / or general populace education uses (e.g., Leslie *et al*., 2012).

2.2. Pre-thrust template controls

Controls on the location of cross-strike discontinuity phenomena, cross-strike linkages and transverse zones are complex. In many cases, causative structures for lateral changes are often concealed either by distal parts of the thrust belt or by the foreland basin (Brown *et al*., 1997; Pérez-Estaún *et al*., 1997). However, many studies have identified that transverse zone development may occur as a result of pre-, syn-, and / or post-orogenic influences incorporating pre-thrust template architecture, and syn-kinematic responses including along-strike variations in sole-thrust and thrust sheet propagation / cessation rates (e.g., Morley, 1986a; Bonini *et al*., 2010). Such variations have important consequences on the structural architecture of the fold-thrust belt, causing lateral variations in horizontal shortening, deformation style and spatial organisation of transport-transverse structures (e.g., Turner *et al*., 2010).

Importantly, many cross-strike discontinuities and transverse zones have been found to be located over long-lived pre-thrust zones of weakness which have controlled subsequent lateral variations in basin geometry, and across which there is dramatic differences in stratigraphy (e.g., Kulik & Schmidt, 1988; Thomas, 1990; Mitra, 1997; Pérez-Estaún *et al*., 1997; Paulsen & Marshak, 1997; 1998; Kley *et al*., 1999; Mouthereau *et al*., 2002; Giambiagi *et al*., 2008; Bonini *et al*., 2010). Along-strike partitioning of thrust belts at transverse zones occurs at a range of spatial scales from crustal-scale salients and re-entrants, which create a smooth change in thrust architecture involving thrust front curvature (e.g., the Appalachians; Tull & Holm, 2005), to drastic sinuosity along individual map-view thrust traces (e.g., Kley *et al*., 1999; Cook, 2010; Mescua *et al*., 2010; Aschoff *et al*., 2011). Large-scale causes of transverse zones may include:

- Pre-deformational characteristics of the sedimentary basin such as basin-controlled deflections, (e.g., Bonini *et al*., 2010; Mescua *et al*., 2010 and references therein),
- Hinterland collision of an indenter such as the India-Asia collision (McDougall & Khan, 1990),
- Irregularities on colliding margins, i.e., major transform fault alignments along the Laurentian rifted margin producing promontories and embayments, such as the Alabama Promontory and Ouachita Embayment, creating transverse zones in Georgia and Alabama (e.g., Cartersville, Rising Fawn and the Anniston, Bessemer, Harpersville respectively) along the Birmingham Graben system (Thomas, 1977; 1991; 2004; 2007; Kley *et al*., 1999; Brewer, 2004, Bayona & Thomas, 2006; Cook, 2010; Figure 2.6),
- Post-orogenic thrust belt interactions with strike-slip faults (e.g., Kley *et al*., 1999),
- Superposition of secondary deformation events with tectonic transport directions oblique or perpendicular to that responsible for initial thrust belt formation, such as far-field vertical-axial rotations or secondary 'oroclinal' bending (e.g., Poblet & Lisle, 2011).

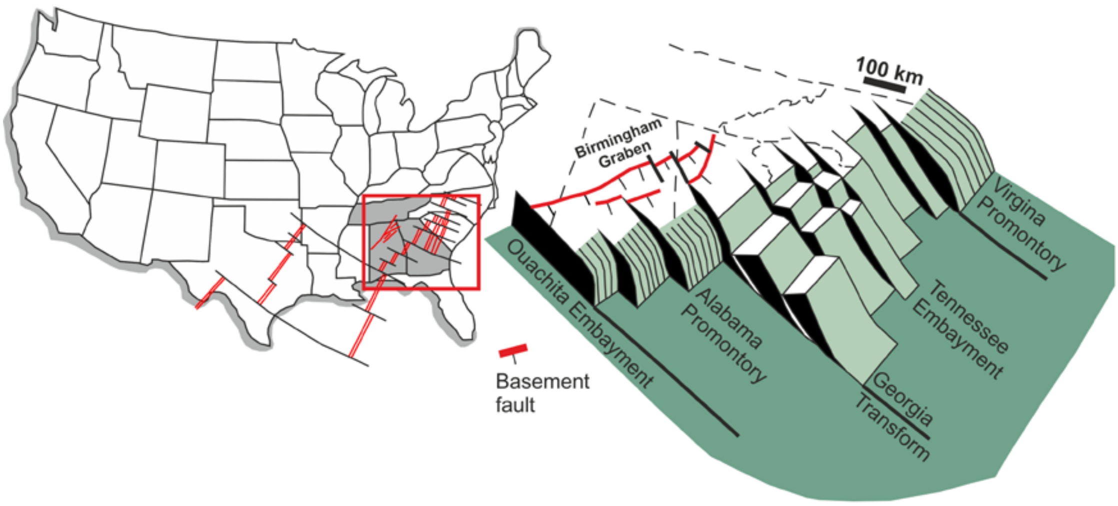


Figure 2.6: Block diagram facing northwest showing marginal and intraplate basement structural geometries along the southern Laurentian passive margin illustrating major transform faults, promontories and embayments beneath the Appalachian fold-thrust belt (Adapted after Bayona & Thomas, 2006). Insert shows relative position of southern Laurentian margin within the USA.

Thomas (1990) and Krabbendam & Leslie (2010) reviewed systematic alignments of cross-strike discontinuity phenomena and cross-strike linkages into transverse zones. These studies, and further examples identified within this review, suggest several smaller scale controls within pre-thrust template geometries which influence the development of syn-kinematic cross-strike discontinuity phenomena within transverse zones including:

- Kinematic responses to irregularities generated across pre-existing, sometimes re-activated, pre-, syn- and post-depositional sub-décollement basement faults (e.g., reactivation of inheritance structures; the role of buttressing, transpression and transtension in duplex / antiformal stack formation; culmination development and vertical-axial rotations (e.g., Lis & Price, 1976; Benvenuto & Price, 1979; Wiltschko & Eastman, 1983; Skuce *et al*., 1987; Couples & Lewis, 1988; Kulik & Schmidt, 1988; Sanderson & Spratt, 1992; Lawton *et al*., 1994a; 1994b; 1996; MacKay *et al*., 1994; McMechan, 1995; Spratt *et al*., 1995; Bégin *et al*., 1996; Lebel *et al*., 1996; Soule & Spratt, 1996; Stockmal *et al*., 1996; Pérez-Estaún *et al*., 1997; Paulsen & Marshak, 1997; 1998; Fermor, 1999; Kley *et al*., 1999; Tull & Holm, 2005; Bonini *et al*., 2010; Mescua *et al*., 2010; Di Domenica *et al*., 2012a; 2012b).

- Along-strike variations in mechanical stratigraphy and / or lithofacies in the deforming sedimentary wedge, i.e., along-strike rheological changes, lateral thinning, facies changes and pinch-outs of favourable décollement-host strata; thrust sheet vertical competency variations and lateral changes in depth to detachment (e.g., Rodgers, 1963; Miller, 1973; Woodward, 1987a; Woodward *et al*., 1988; DeCelles *et al*., 1995; Brewer, 2004; Cook, 2010; Bigi *et al*., 2009; Pace *et al*., 2012b).

- Contrasts in pre-thrusting deformation of cover strata above basement faults (e.g. Liu *et al*., 1992; Marshak *et al*., 1992; Macedo & Marshak, 1999; Butler *et al*., 2006; Sepehr *et al*., 2006; Turner *et al*., 2010).

- Combinations of both structural and stratigraphical variations i.e. basement and cover interactions, basement highs and thick-, thin-skinned deformation styles (e.g., McLaren, 1955; Hargreaves, 1959; Thomas, 1990; Ross *et al*., 1991; Eaton *et al*., 1995; Brandley *et al*., 1996; Cecile *et al*., 1997; Spratt & Dixon, 1999; Bégin & Spratt, 2002; Mouthereau *et al*., 2002; Giambiagi *et al*., 2008).

2.2.1. Pre-thrust template controls: Sub-décollement basement faults

Interpretations of fundamental causes of cross-strike discontinuities and transverse zone locations commonly focus on faults within basement rocks below the décollement (e.g., Kulik & Schmidt, 1988; Couples & Lewis, 1988; Bayona, 2003). Thomas (1990) identified that genetic relationships between sub-décollement basement faults and transverse zone formation are variable and that correlations are only possible based upon local geology and available evidence. Where pre-existing basement faults are invoked as a parent structure to a transverse zone, contact of the transverse zone with the basement is commonly concealed by external parts of the thrust belt or by its foreland basin due to large amounts of displacement (Brown *et al*., 1997; Pérez-Estaún *et al*., 1997). Only a few thrust belts globally, such as the Palaeozoic Uralide Orogen, allow detailed studies to be achieved as a result of low displacements within the frontal portions of the orogen (e.g. Nalivkin & Yarobson, 1985; Rodgers, 1990; Brown *et al*., 1997; Pérez-Estaún *et al*., 1997).

Studies considering regional geometrical architectures and kinematics within transverse zones, and thrust belts as a whole, have emphasised that knowledge of pre-existing allochthon external sub-décollement basement fault configurations and their pre-, syn-, and / or post-stratigraphical depositional impacts on the pre-thrust template are essential for understanding transverse zone development (e.g., Rankin, 1976; Thomas, 1977; Schwartz & Van der Voo, 1983; Kent, 1988; Stamatakos & Hirt, 1994; Stamatakos *et al*., 1996; Bayona & Thomas, 2006; Figure 2.7a-c). Conversely, where no basement faulting is present, lateral variations in mechanical stratigraphy and stratigraphical thickness control transverse zone development (Thomas, 1990; Figure 2.7d).

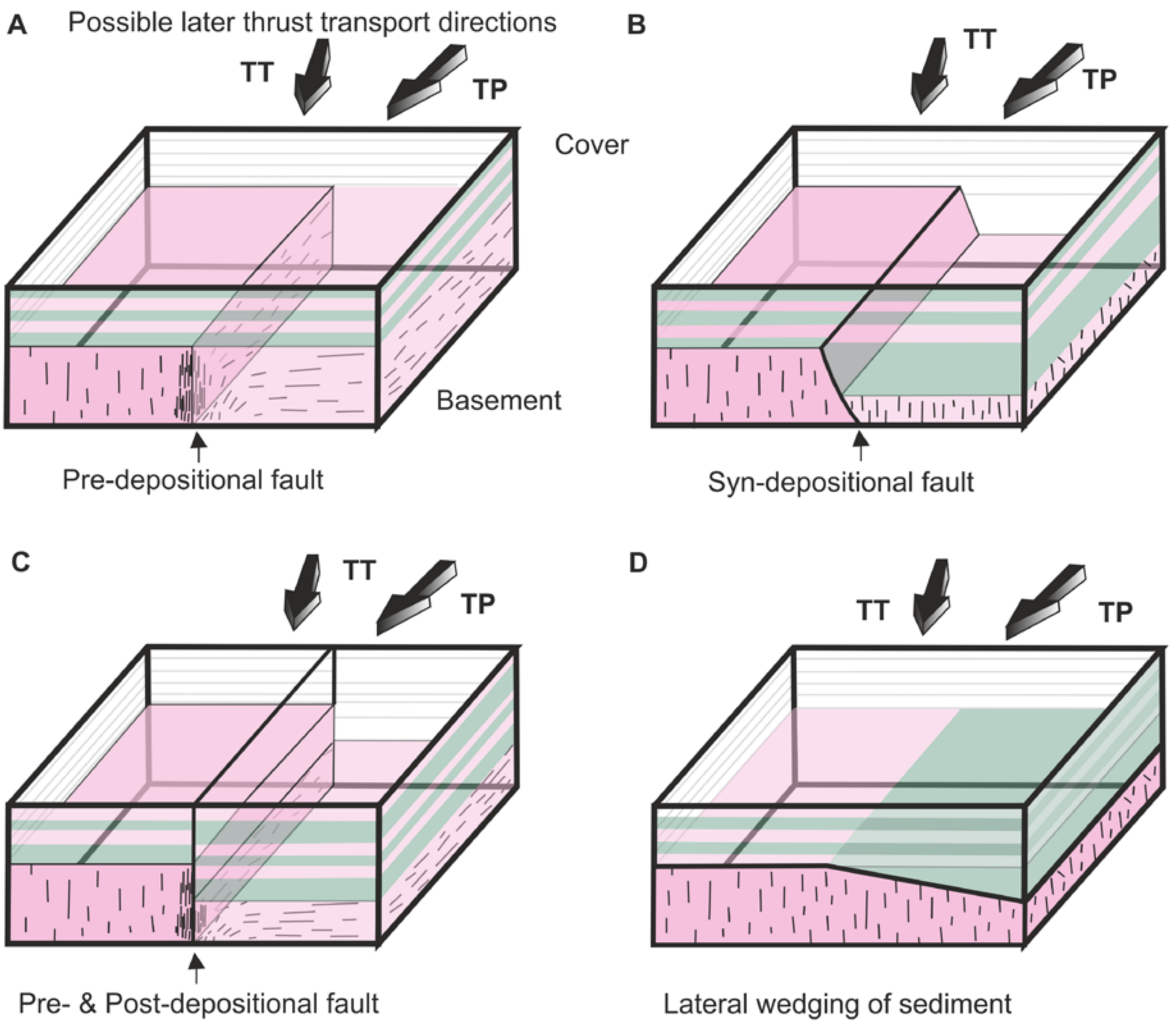


Figure 2.7: Possible lateral variations in pre-thrust templates. **(A)** pre-depositional fault in basement, not displacing cover strata; **(B)** syn-depositional fault within the basement, active during cover strata deposition; **(C)** pre- and post-depositional fault within basement displacing the cover strata after deposition. **(D)** lateral wedging of sediment. Note that different combinations are likely within nature, whilst different angles between the feature and the subsequent thrust transport direction (arrows) can lead to localised transpression (TP) or transtension (TT) (Adapted after Krabbendam & Leslie, 2010).

2.2.1.1. Pre-depositional basement faults

Pre-depositional basement faults do not affect overlying cover strata, creating a flat unconformity (i.e., without post-depositional displacement; Figure 2.7a). Such a structure would only affect thrust architecture if thrusting incorporated basement (i.e., thick-skinned thrusting; e.g., the Laramide Orogeny; Schmidt *et al*., 1993 *in* Poblet & Lisle, 2011). Additional effects may develop if a distinct difference in orientation of the principal basement fabric is present, for instance, if the fabric is sub-horizontal on one side and sub-vertical on another (e.g., Bégin & Spratt, 2002; Konstantinovskaya *et al*., 2007 and references therein; Figure 2.7a). Along-strike variations within the Moine Thrust Belt across the Laxford Shear Zone (e.g., Beach *et al*., 1974; Goodenough *et al*., 2010; Krabbendam & Leslie, 2010) and the Ballabio-Barzio Transverse Zone, Southern Alps, northern Italy (e.g., Laubscher, 1985; Schönborn, 1990, 1992) illustrate such examples.

2.2.1.2. Syn-depositional basement faults

Vertically stacked, geographically coincident stratigraphical thickness variations at several levels within a stratigraphical succession indicate episodic reactivation of a basement fault (i.e., a syn-depositional fault; Trumbo, 1976; Baars & Stevenson, 1982; Rees, 1986; Thomas, 1986; Figure 2.7b). Within this example, the basement fault is active during cover strata deposition.

Paulsen & Marshak (1998) identify syn-depositional basement faulting within the Sevier fold-thrust belt, Utah, USA, across the Charleston Transverse Zone. Along-strike stratigraphical thickness variations within Proterozoic to Permian strata from three to nine kilometres were documented. On the down-thrown side, where the sedimentary package is thickest, thrusts propagated farthest onto the foreland involving thick thrust sheets, comprising only sedimentary strata. Conversely, on the up-thrown side, basement slices are incorporated within thrusting (Paulsen & Marshak, 1998).

Similar observations are identified within the Anniston Transverse Zone, Alabama, USA, where Cambrian to Mississippian strata indicates episodic reactivations during deposition along syn-depositional basement faults (e.g., Thomas, 1986; Ferrill, 1989; Thomas *et al*., 2000; Thomas & Bayona, 2002). Conversely, within the Bessemer Transverse Zone and Black Warrior Basin, Alabama, USA, the Birmingham Graben basement faults indicate episodic reactivations affecting the oldest clastic units the most, whilst overriding Mississippian carbonate successions remain laterally continuous, and are not affected by basement obstacles (e.g., Thomas, 1985; Pashin *et al*., 2010). Further examples illustrating along-strike changes in stratigraphical thickness attributed to syn-depositional faults are identified within the:

- Cordilleran fold-thrust belt, western USA, (e.g., Lawton *et al*., 1994a),
- Apennine fold-thrust belt, Italy (e.g., Butler *et al*., 2006),
- West Virginian and northern Pennsylvanian Appalachian fold-thrust belt (e.g., Tyrone-Mount Union Transverse Zone; Lavin *et al*., 1982; Rodgers & Anderson, 1984; Wheeler, 1986),
- Canadian Rockies (e.g., Montana Transverse Zone; McMannis, 1963; Schmidt, 1976; Meyers, 1980; 1981; Schmidt & O'Neill, 1982; Schmidt *et al*., 1988; Ross *et al*., 1991; Eaton *et al*., 1995; Brandley *et al*., 1996; Cecile *et al*., 1997; Spratt & Dixon, 1999; Bégin & Spratt, 2002).

Syn-depositional basement faults not only impact upon stratigraphical thickness, but also upon along-strike facies variations (e.g., along-strike sediment point source alternations within the Sevier fold-thrust belt; Aschoff *et al*., 2011). Further examples are identified within the Zagros and Appalachian fold-thrust belts (e.g., Thomas, 1977; 1982; 1985; 1986; Ferrill, 1989; Rich, 1992; Thomas *et al*., 2000; Thomas & Bayona, 2001; 2002; Brewer, 2004; Yassaghi & Madanipour, 2008; Cook, 2010; Pashin *et al*., 2010; Turner *et al*., 2010). Rich (1992) documented basement fault configurations in north-western Georgia, USA, based on the location and orientation of surface structures and Mississippian facies changes. Rich (1992) interpreted steep basement fault reactivations intermittently during the Palaeozoic, thereby significantly influencing the geometry and location of Appalachian folds (i.e., drape folds) and faults, as well as the depositional framework, especially during the Mississippian Period (e.g., Cook, 2010).

Episodic, syn-sedimentary basement fault movements have two alternative implications for controls on transverse zone nucleation within a subsequent thrust belt:

1. Deflection of the décollement to a different stratigraphical level due to lateral changes in décollement-host strata (e.g., Ligurian Alps; Bonini *et al*., 2010),

2. Deflection of décollement due to a fault or flexure in cover strata over a basement fault (e.g., Caquerelle and Erschwil Lines, Himalayan foreland, Pakistan and Rheintal Jura Mountains respectively; Laubscher, 1981; McDougall & Khan, 1990; Thomas, 1990).

However, combinations of the two alternatives can be identified in nature over varying temporal and spatial scales where large vertical separations can be observed (e.g., Homer and St. Mary and Moyie Faults; Price, 1967; 1981; Price *et al*., 1972; Lis & Price, 1976; Benvenuto & Price, 1979).

2.2.1.3. Post-depositional basement faults

Post-depositional basement faults are faults which affected overlying strata after deposition, so that cover strata rest upon an unconformity, which is subsequently displaced creating a pre-thrust compartmentalisation along-strike (Figure 2.7c). This type of fault would have an effect on thrust architecture not only if thrusting affected cover rocks, but also if it affected cover and basement (e.g., Traligill Transverse Zone, Assynt Culmination, Moine Thrust Belt, Northwest Highlands, Scotland; Krabbendam & Leslie, 2010).

The Traligill Transverse Zone developed sub-parallel to, and structurally above, a pre-existing sinistral fault (i.e., Loch Assynt Fault) displacing both basement and cover prior to thrusting. No stratigraphical changes occur across the fault; therefore it is post-depositional, although it reactivated the long-lived ductile Proterozoic Stoer Shear Zone identified within Lewisian basement (Krabbendam & Leslie, 2010).

Similarly, regional gravity modelling data have been used to argue that the Oykel Transverse Zone within the southeast Assynt Culmination of the Moine Thrust Zone, was generated above an underlying ramp within the basement-cover interface (Leslie *et al*., 2010). This ramp is interpreted as the result of reactivation of a west-northwest to east-southeast trending sub-vertical basement shear zone, the Canisp Shear Zone. These examples illustrate a reactivation of basement faults with pre- and post-depositional elements (Figure 2.7c). Further examples are documented within the Canadian Rockies along Proterozoic basement shear zones beneath the Montana Transverse Zone (e.g., Ross *et al*., 1991; McMechan, 2002; Bégin & Spratt, 2002; Pană, 2003).

Calassou *et al*., (1993) used sand box modelling to study post-depositional fault effects, such as the Loch Assynt Fault within the Traligill Transverse Zone, identifying similar traits to syn-depositional faults including:

- Lateral interfingering of thrust sheets, both in map-view and in cross-section along the transverse zone,
- Thrusts developing above the down-thrown side of the basement fault propagating further on the foreland, defining a bend in the thrust front,
- Different thrust geometries in the compartments on either side of the transverse zone, with fewer but thicker thrust sheets on the down-thrown side.

Syn- and post-depositional fault differences are therefore complex to identify. Indeed, numerous hybrid varieties between pre-, syn- and post-depositional faults may be produced depending on localised structural and stratigraphical conditions (Kanasewich *et al*., 1969; Price, 1981). If there is a relationship between pre-existing basement faults and transverse zones, the following hypotheses may be viable:

- Thrust faults are deflected over an irregular, faulted, basement surface;
- A décollement-host stratigraphy that is deformed by pre-existing basement structures may partition advancing thrust sheets;
- Drape folds in the cover strata may deflect advancing thrust faults;
- Thrust surfaces may be displaced by a still active, underlying basement fault.

2.2.2. Pre-thrust template controls: Mechanical stratigraphical deposition

Along-strike variations in stratigraphical thickness and mechanical behaviour not related to basement faults also play a key role in subsequent cross-strike discontinuity / transverse zone development (Figure 2.7d). However, such changes are not necessarily aligned with thrust direction, nor concentrated along a particular zone. Along-strike variations would be expected to have a gradual, tapering effect on overall thrust geometry, a good example being the study of Soto *et al*., (2002) within the southern Pyrenees. However, if lateral facies changes involve easy glide horizons (e.g., siltstones or evaporites) the effects may be more pronounced. Woodward (1988) proposed that areal and vertical locations of thrust ramps and flats within subsequent thrust systems were controlled in greater proportion by stratigraphical packaging rather than by basement-fault proximity or geometry.

Woodward *et al*., (1988) identified that where stratigraphical cover unit properties are regionally non-uniform, stratigraphical changes occur in greater proportions. Strike-parallel stratigraphical variations in the décollement-host stratigraphy including, along-strike changes in stratigraphical thickness and / or pinch outs of stratigraphical units (e.g., thinning and / or loss of a glide horizon), as well as, along-strike facies changes of décollement-host strata will impact greatly on the origin and evolution of subsequent thrust structures. Such along-strike variations may cause deflections of a thrust surface into more favourable strata (e.g., Rodgers, 1963; Miller, 1973; Woodward, 1987b; Woodward *et al*., 1988; Butler, 1989; Thomas, 1990; 2004; Brewer, 2004; Bigi *et al*., 2009). This may be due to differential compaction depending on palaeogeographical settings, basement highs within the foreland, or an irregular basement surface (e.g., Butler, 1989; Thomas, 1990; Bigi *et al*., 2009).

Thrust sheet bulk stratigraphy is directly related to mechanical properties of the pre-thrust basin stratigraphical deposits, and is therefore a primary factor in how thrust sheets deform (Woodward, 1987b). Alternations of rigid and weak layers control partitioning of brittle and ductile deformation with respect to depth within a thrust sheet (e.g., Hatcher *et al*., 1989; Chester & Chester, 1990; Chester *et al*., 1991; Mitra, 2005; Pace *et al*., 2012b). Therefore, along-strike variations in mechanical behaviour act as pre-thrust template weaknesses, or deformation focal points, for subsequent thrust sheet development and along-strike variations in deformation style (e.g., Suppe, 1983; Suppe & Medwedeff, 1990; Thomas, 2001; 2007; Poblet & Lisle, 2011 and reference therein). Examples of these controls are documented within Appalachian transverse zones, where thick Cambro-Ordovician carbonate successions control structural style (e.g., Anniston Transverse Zone; Thomas, 1985), and within Andean transverse zones (e.g., Mescua *et al*., 2010).

Along-strike variations in depth to potential décollement-host strata have also been found to play a key role in cross-strike discontinuity / transverse zone location (e.g., Marshak & Wilson, 1992; Macedo & Marshak, 1999; Figure 2.8; 2.9). Models within Liu *et al*., (1992) and Turner *et al*., (2010) which focus on the Keping Shan Thrust Belt, demonstrate that along-strike lateral partitioning is strongly affected by lateral variations in sediment thickness above the detachment horizon. Where pre-thrust template thicknesses are abrupt (i.e., basement-fault induced) strike-slip / transverse faults are produced (Figure 2.8a), whereas abrupt, but minor changes, in stratigraphical thickness caused either by a basement fault or stratigraphy, result in thrust branching rather than compartmentalisation faulting (Figure 2.8b).

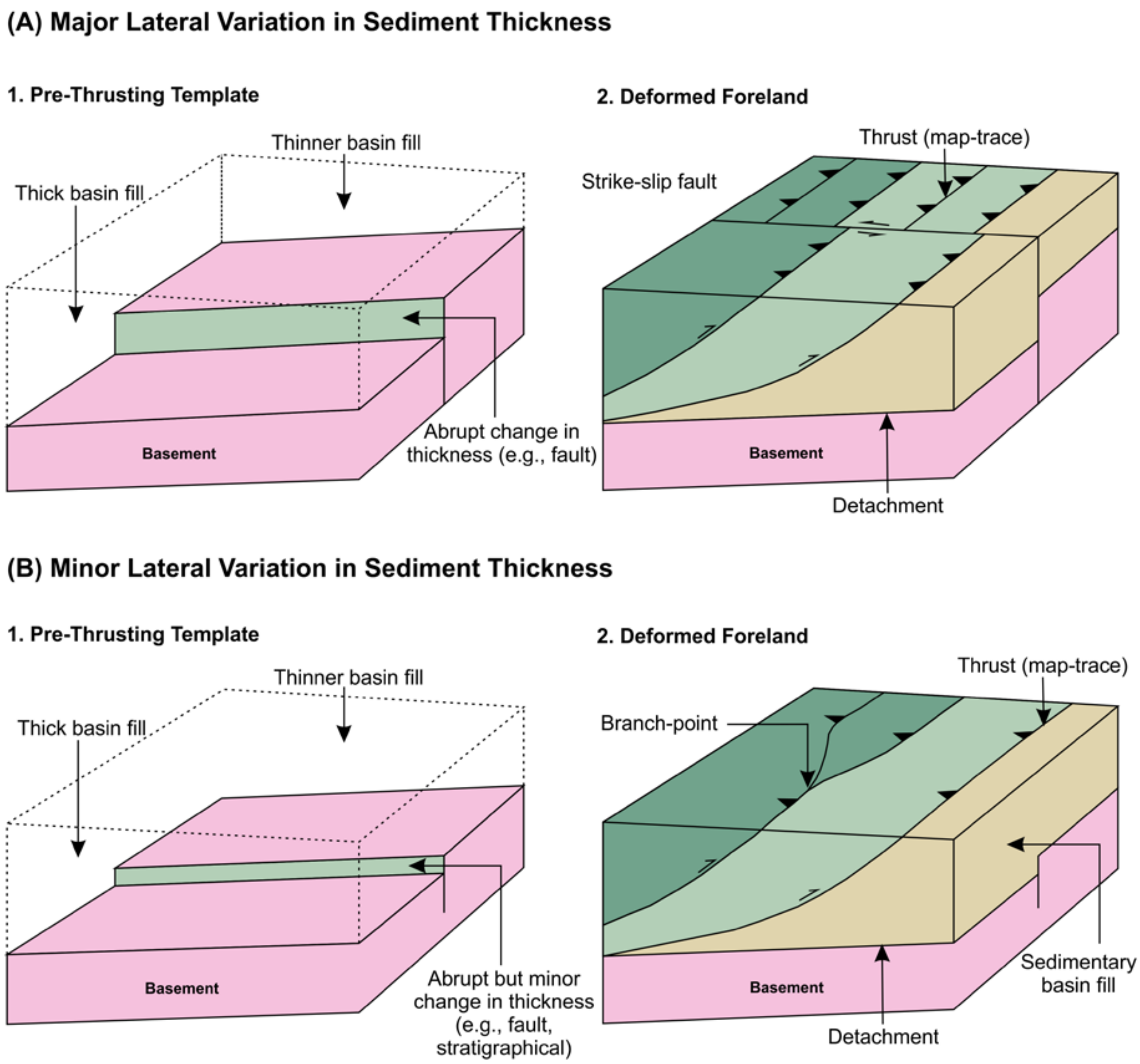


Figure 2.8: Impact of sediment thickness on thrusting: **(A)** Abrupt and substantial lateral change across a major pre-existing fault zone, resulting in fault reactivation and lateral partitioning of the thrust belt; **(B)** Abrupt but small change across a pre-existing fault zone or stratigraphical thickness, causing a kink or branching of superimposed thrusts without the necessity for fault reactivation (Turner et al., 2010).

Further models within Bigi *et al*., (2009) have demonstrated that thickness variations within the pre-thrust template, with or without subsequent basement structures, play a first-order role in determining the three-dimensional architecture of resulting orogenic belts and transverse zones. Where stratigraphical thickness variations are greater, subsequent thrust faults are widely spaced, thrust sheets are thicker and are mainly shallowly dipping. Conversely, where thinner sequences are involved, subsequent thrust faults are closely spaced, forming imbricate fans of more steeply dipping thrust sheets (Pohn, 1998). Along-strike alternations between the two states create cross-strike discontinuities (e.g., central

Fars area transverse zones, Iran; Motamedi *et al*., 2012). Observations documenting along-strike variations are also dependent on three-dimensional erosion level expressions viewed within the stratigraphical sequence (e.g., Pohn, 1998; Figure 2.9). Along-strike variations in lithological thicknesses, not related to basement faulting, have been extensively applied to salient and recess formation within the southern Appalachian Thrust Belt (e.g., Thomas, 1977; 1985; 2004; Tull & Holm, 2005; Cook, 2010).

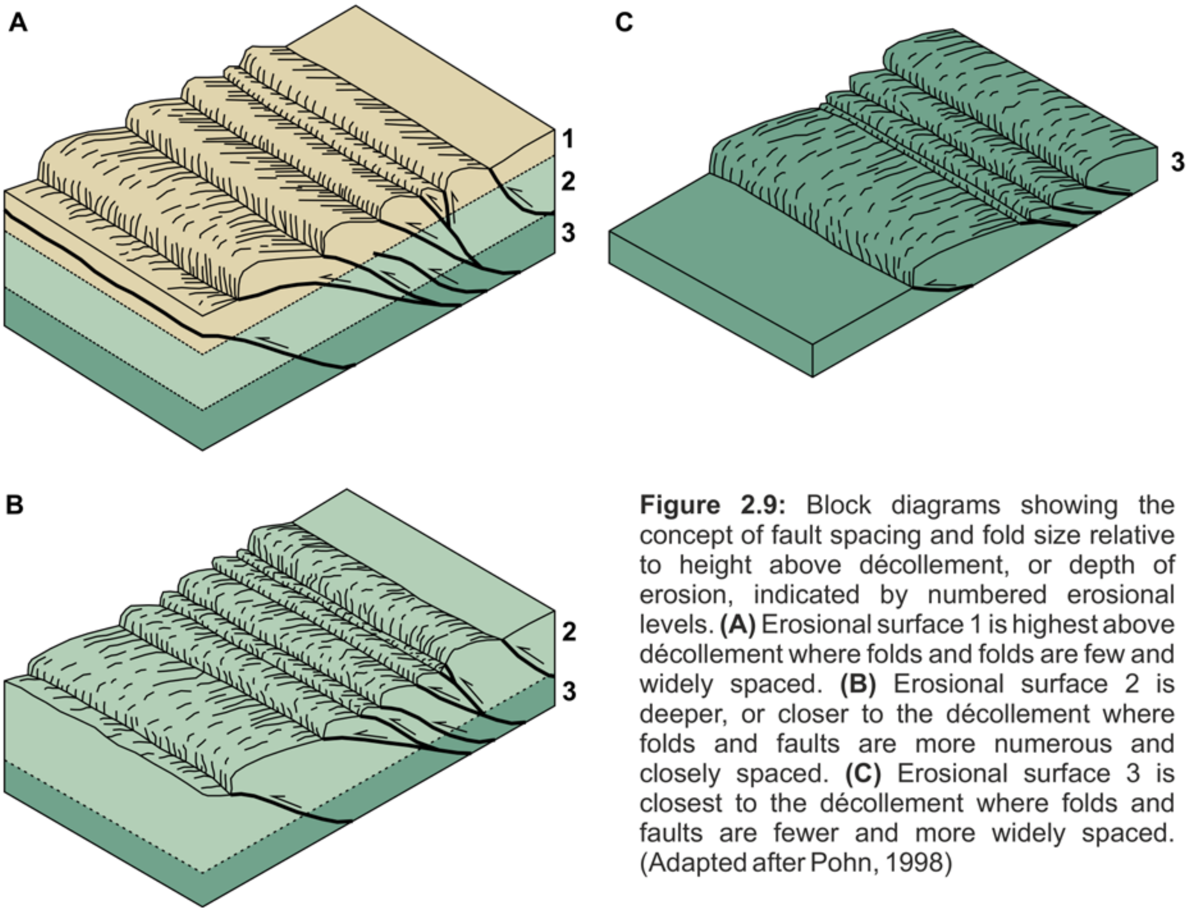


Figure 2.9: Block diagrams showing the concept of fault spacing and fold size relative to height above décollement, or depth of erosion, indicated by numbered erosional levels. **(A)** Erosional surface 1 is highest above décollement where folds and folds are few and widely spaced. **(B)** Erosional surface 2 is deeper, or closer to the décollement where folds and faults are more numerous and closely spaced. **(C)** Erosional surface 3 is closest to the décollement where folds and faults are fewer and more widely spaced. (Adapted after Pohn, 1998)

The extent to which pre-existing structures and / or stratigraphical variations control the location of cross-strike linkages and cross-strike discontinuity phenomena is still debated. It is not abundantly clear which (structure or stratigraphy) exerts the dominant control on cross-strike discontinuity initiation. However, a compromise is accepted where both factors are acknowledged as having an impact, the severity of which is dependent on local factors (Brewer, 2004).

2.3. Syn-kinematic implications: Cross-strike discontinuity phenomena

Structural and stratigraphical pre-thrust template controls play a crucial role on the syn-kinematic plan of cross-strike discontinuities (CSDs), transverse zones and thrust belts as a whole (Thomas, 1990; Brewer, 2004). Although Woodward *et al*., (1988) identified that along-strike variations in mechanical stratigraphy and thickness play a key role in thrust ramp and flat formation within subsequent thrust sheets where no basement fault is required; production of cross-strike discontinuity phenomena (i.e., along-strike map-view representations of subsurface structural and / or stratigraphical irregularities aligned within transverse zones), commonly hinges on the relationship between thrust translation (i.e., regional transport) and orientation to pre-existing basement structures during allochthon formation (e.g., Laubscher, 1985; Thomas, 1990). Thomas (2007) identified that thrust translation and pre-thrust stratigraphical gradient relationships were also important.

Laubscher (1985) identified that during subsequent thrusting, pre-thrust structures within the Southern Alps, northern Italy, guided separate kinematic developments within different transverse-zone-bound segments of the thrust belt depending on thrust transport angularity against pre-existing structures. Basement structures striking 90° to transport may be reactivated. Conversely, where transport is oblique to a pre-existing basement structure or along-strike rheological change, thrust systems may 'lock-up' creating localised zones of buttressing and / or deflections of thrusts and folds as a result of transpression or transtension (Krabbendam & Leslie, 2010). Therefore, cross-strike discontinuity phenomena are produced as a result of reactivation of pre-existing structures, buttressing against pre-existing structures, and / or thrust and folds deflections over such structures. Cross-strike discontinuity phenomena include: lateral / oblique ramps, transverse faults, duplexes / antiformal stacks, geological windows, culmination walls and deflected thrusts / folds associated with vertical-axial rotations of thrust sheets.

Thomas (1990) identified post-thrusting cross-strike discontinuity phenomena positions; recognising that fault-bounded irregularities on the autochthonous basement surface control location of thrust ramps formed at the site of allochthon emplacement over basement faults. Cross-strike linkages or cross-strike discontinuity phenomena so formed would remain above the parent basement fault (e.g., lateral ramps and / or lateral culmination walls; Figure 2.10). A cross-strike linkage or cross-strike discontinuity in cover strata deformed by a basement structure striking parallel to thrust displacement will be located along the strike-parallel projection of the basement structure; however, where translation vector of allochthon displacement is oblique to basement structure orientation, cross-strike linkages or cross-strike discontinuity phenomena would be translated to a

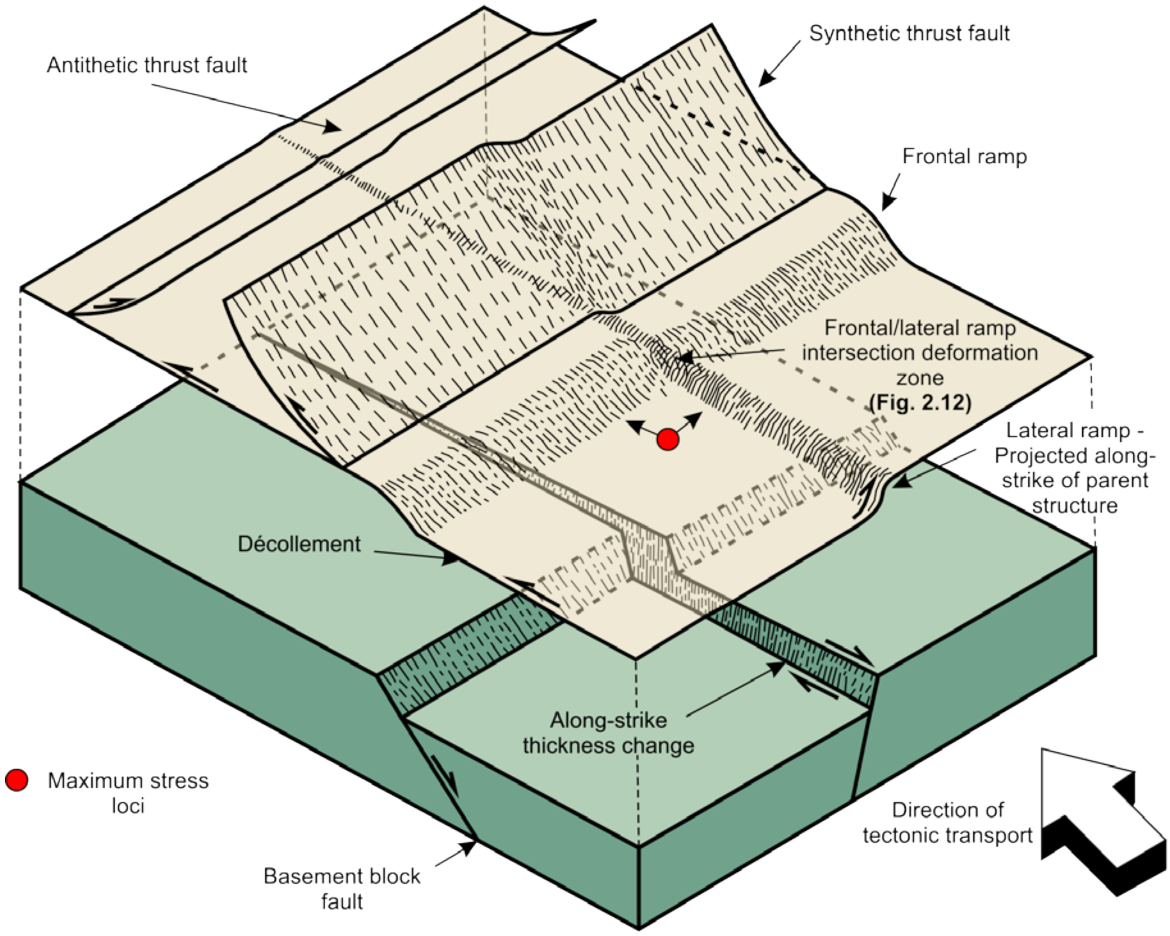


Figure 2.10: Block diagram showing relationship between basement block faults, frontal ramps, basement cross-strike faults and lateral ramps. Final post-thrusting projections of cover deformation structures are also illustrated. Maximum stress loci (i.e., regions of maximum deformation) within the cover are identified close to subsurface structures. Arrows indicate relative movement (Adapted after Pohn, 1998).

position oblique to the basement structure strike (Wheeler, 1986; Thomas, 1990; Brewer, 2004). Cross-strike linkages and cross-strike discontinuity phenomena initiated by pre-thrusting stratigraphical variations would, however, be translated farther cratonward during thrusting (e.g., Wheeler, 1986; Thomas, 1990; Brewer, 2004).

In linear, regionally non-transpressional, mountain belts such as the Moine Thrust Belt, Northwest Highlands, Scotland, determination of tectonic transport is relatively straightforward as major thrusts and folds strike normal to thrust transport (Leslie *et al*., 2010). As such, lateral structures and cross-strike discontinuity phenomena are easily identified (e.g., Traligill and Oykel Bridge Transverse Zones; Krabbendam & Leslie, 2010; Leslie *et al*., 2010). Lateral structures and cross-strike discontinuity phenomena within complex arcuate mountain belts (i.e., oroclines, Carey, 1955), such as the Cantabrian Arc, are harder to identify as thrust and fold trend variations may result from at least two different mechanisms:

1. The orogenic belt was initiated with its present curved form and built up with a constant transport direction during thrusting, or

2. Resulted from superposition of a later strain on a previous generation of faults / folds, causing migration of cover deformation from parental controlling structures (e.g., Frizon de Lamotte & Guezou, 1995; Marshak, 1998; Cook, 2010).

To determine the role of thrust translation against pre-existing transverse structures within the Moine and Cantabrian thrust belts, pertinent discussions are required for syn-kinematic cross-strike discontinuity phenomena produced during allochthon formation as a result of structural reactivations, along-strike buttressing and deflections as a result of transpression, transtension and vertical-axial rotations.

2.3.1. Role of thrust translation alignment: Reactivation of pre-existing structures

Many papers, based on field experience or seismic data interpretation, have documented contractional reactivation of pre-existing normal and / or strike-slip faults bordering sedimentary basins which have experienced pre-, syn- and / or post-depositional movements (e.g., Bonini *et al*., 2010 and references therein). Reactivation depends on many factors including; fault strike orientations with respect to newly imposed stress fields, geometrical features of pre-existing faults, migration of flexural loading and rheology of involved stratigraphical sequences (e.g., Etheridge, 1986; Gillcrist *et al*., 1987; McClay & Buchanan, 1991; Coward, 1994; Mouthereau *et al*., 2002; Konstantinovskaya *et al*., 2007; Cook, 2010; Calamita *et al*., 2011; Poblet & Lisle, 2011).

Wiltschko & Eastman (1983; 1988) documented how basement warps and faults concentrated stress in immediately overlying cover rocks using two-dimensional, two-layer photoelastic models. Results of the experiments indicate that pre-existing basement faults constitute a rigid surface against which principal stress trajectories bend, hence deflecting propagating faults (Brewer, 2004). Furthermore, models illustrate maximum stress intensities above the crests of pre-existing anticlines and up- or down-thrown basement fault blocks where the stratigraphical section is thinnest (Figure 2.10). Fault initiation will therefore occur at the maximum stress loci, whilst thrust propagation is bi-directional. Good examples of this can be observed within southern Appalachian transverse zones, where basement faults have localised thicker Cambrian shale sequences producing ‘mushwads’ (i.e., tectonically thickened, ductilely deformed duplexes; e.g., Gadsden, Palmerdale and Bessemer mushwads; Thomas, 2001; 2007; Thomas & Bayona, 2002; 2005).

Basement structures aligned favourably to the newly imposed compressional stress field may be reactivated as reverse structures during early pulses of the orogeny. However, it must be noted that contractional deformation would only convert a transfer fault into a lateral ramp if the vector of thrust displacement was nearly parallel to the strike of the original ramp (Figure 2.10). Otherwise, the transfer fault would become an oblique ramp (Tull & Holm, 2005; Bayona & Thomas, 2006). Large-scale, high-angle, basement faults with significant separation acting as ramps to the overriding thrust sheets also usually exert a significant control on the geometry and spatial distribution of potential hydrocarbon traps (e.g., Berger, 2001).

Pre-existing basement faults located underneath the deforming wedge, and reactivated during the deformation may also result in a transfer of displacement into thin-skinned units, induce out-of-sequence thrusting, either as a result of reactivation of older in-sequence thrusts, or by the development of a new thrust through a deformed thrust sheet; and / or creation of accommodation structures, thereby causing abrupt along-strike structural changes (e.g., Wiltschko & Eastman, 1983; Morley, 1988; Alcicek & ten Veen, 2008).

2.3.2. Role of thrust translation alignment: Buttressing, transpression and transtension

Variations in footwall geometry of frontal, lateral and oblique ramps and their corresponding intersections impact the motion of a hanging-wall over a thrust ramp. Compressional structures (i.e., transpressional structures, such as higher order folds or thrust faults) are generated within overriding hanging-wall strata at the leading frontal ramp intersection with a lateral or oblique ramp creating a structural low if the footwall structure is concave with respect to regional transport (Dewey *et al*., 1998; Figure 2.11).

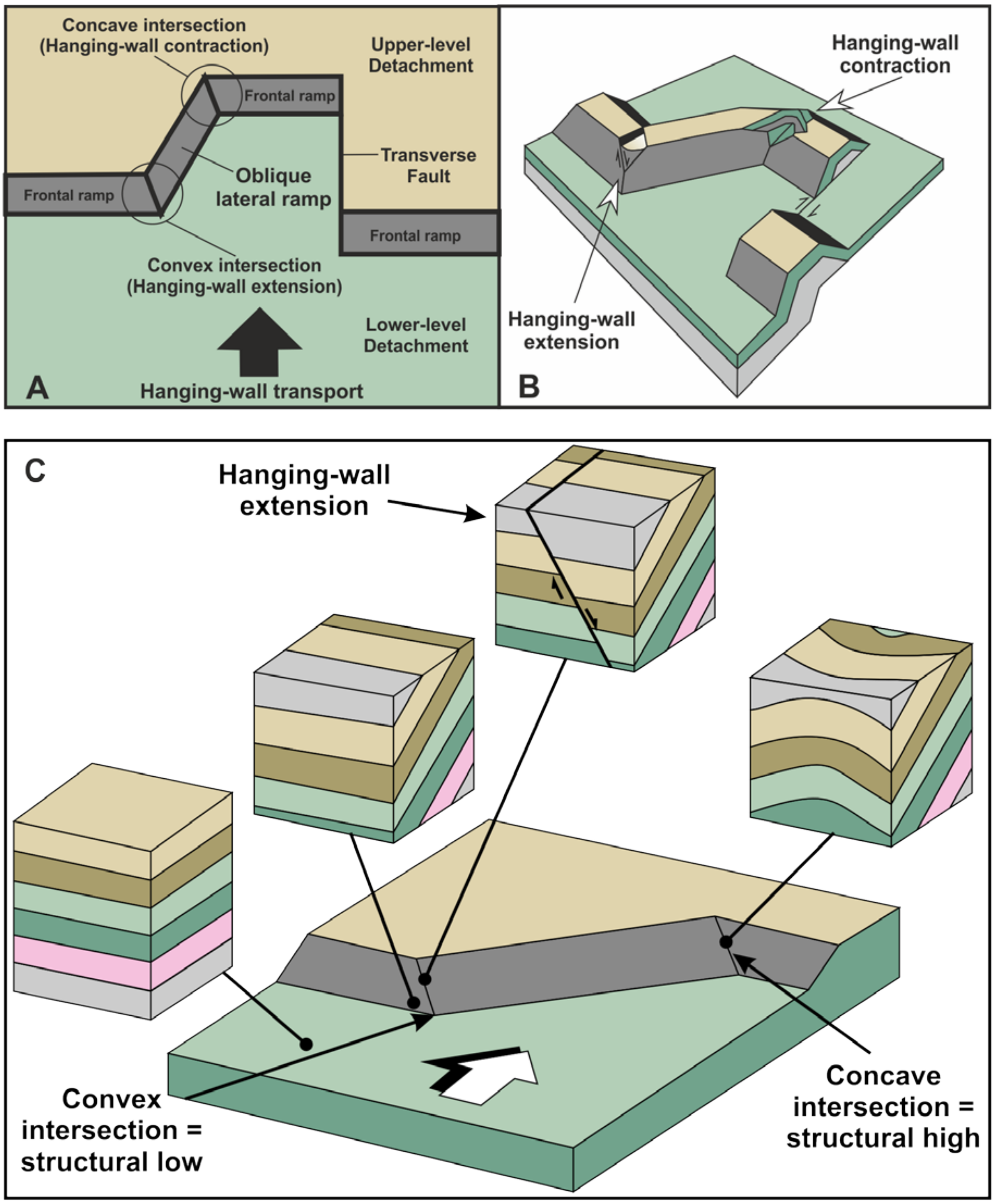


Figure 2.11: (A) Footwall fault geometry (lower-level detachment to ramp to upper-level detachment) at an oblique lateral ramp; the "convex" and "concave" frontal ramp / oblique lateral ramp intersections are labelled; dark polygons show dipping ramp segments. **(B)** Emplacement of hanging-wall rocks over the footwall shown in diagram A; locations of extensional and contractional structures in the hanging-wall are labelled. (**C**) Detailed review of (B); Cover strata deformation over frontal / oblique intersections (Adapted after Apotria, 1990; Apotria *et al.,* 2002).

Conversely, extensional structures and / or tear-faults are formed within the overriding hanging-wall strata at the intersection of a trailing frontal ramp and a lateral / oblique ramp if the footwall structure is convex with respect to the direction of thrusting (i.e., transtension structures; Apotria, 1990; Schönborn, 1992; Dewey *et al*., 1998; Brewer, 2004; Cook, 2010; Figure 2.11).

Thrust ramp intersections also represent areas of increased strain during thrust propagation over lateral or oblique ramps (Apotria, 1990; 1995; Apotria *et al*., 1992; Wilkerson *et al*., 1992; 2002; Brewer, 2004). Where transport is not parallel to the strike of a fault, lateral ramp or basement step, localised transpression and transtension zones are identified (Dewey *et al*., 1998; Krabbendam & Leslie, 2010). Where transport direction is clockwise from the strike of the fault, thrusts need to ramp up and over the basement step, and local transpression is expected (e.g., Charleston Transverse Zone, Paulsen & Marshak, 1998; Figure 2.12). Conversely, if the transport direction is counter-clockwise from the strike of the fault, thrusts would 'descend' the basement step and local transtension is expected (e.g., Dewey *et al*., 1998; Fossen & Tikoff, 1998; Figure 2.12). Well documented examples are identified along the Sangro-Volturno and Olevano-Antrodoco-Sibillini transversal discontinuities within the Apennines, Italy (e.g., Tavarnelli *et al*., 2001; Satolli & Calamita, 2008; Mantovani *et al*., 2012; Pace *et al*., 2012a) and along the Pell City Fault within the Anniston Transverse Zone, southern Appalachians, USA (e.g. Thomas & Bayona, 2002; Bayona, 2003; Cook & Thomas, 2009).

Petrini & Wiltschko (1986) stated that hanging-wall strain, as the hanging-wall moves over a lateral ramp, is controlled by the dip of the fault, changes in ramp amplitude or height along-strike, hanging-wall thickness, and the extent over which stresses are accommodated. These aspects generally all correspond to the magnitude of the underlying basement fault (e.g., Wiltschko & Eastman, 1983; 1988; Apotria *et al*., 1992; Thomas & Bayona, 2002; Thomas, 2007; Figure 2.12). Wilkerson (1991) added that changes in fault dip will generate an oblique ramp, whilst changes in ramp height, either as a result of a basement fault or rheological variations, and detachment level generate lateral ramps. Apotria *et al*., (1992) further quantified this view during kinematical modelling of three-dimensional particle pathways over thrust ramps.

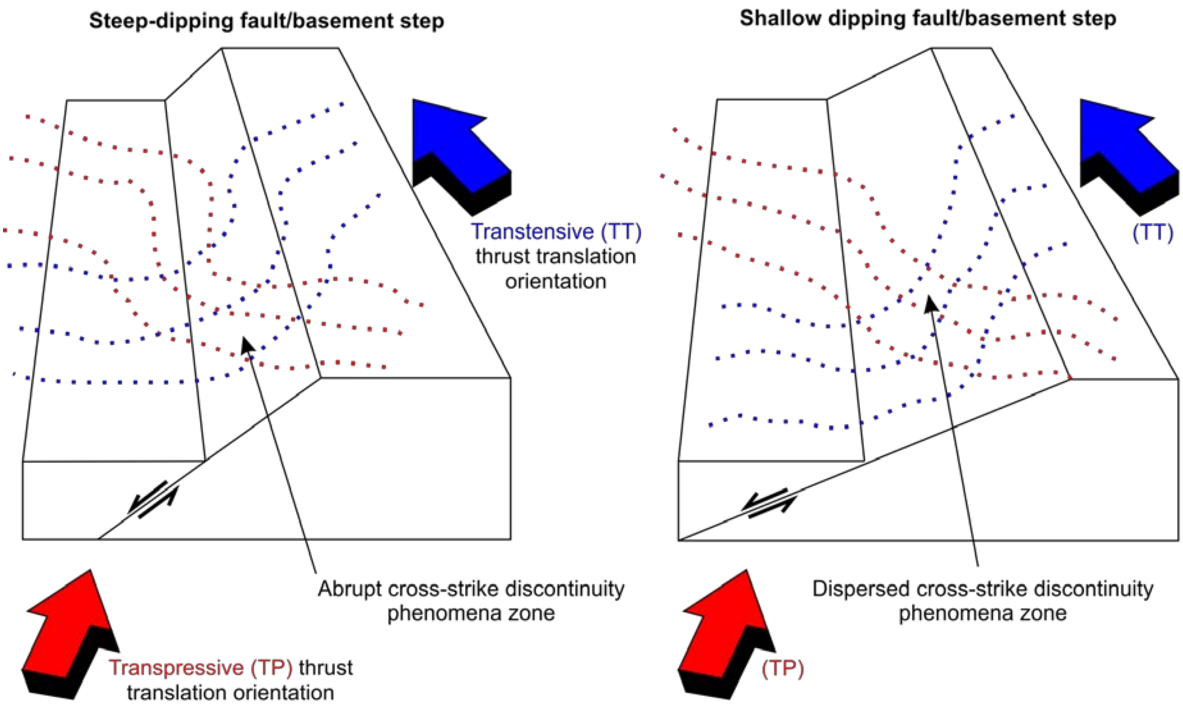


Figure 2.12: Relationship of fault refraction to steepness of fault scarp. Dotted lines represent map-view deformation patterns within the cover over steep and shallow fault scarps. **(A)** Steep faults refract cover deformation steeply creating abrupt compressional or extensional structures in map-view depending on thrust translation orientation (dotted lines, red = transpressive, blue = transtensive). **(B)** Shallow faults refract cover deformation shallowly, creating more subtle map-view compressional or extensional structures depending on thrust translation orientation (dotted lines, red = transpressive, blue = transtensive). Arrows indicate thrust translation orientation: transpression (TP) / transtension (TT) (Adapted after Pohn, 1998).

Ramp height variations produce differing degrees of fault refraction along-strike, as well as differing fold types including, fault-bend folds, culmination walls, and numerous hybrid varieties as folds tighten and lock-up along-strike including, breakthrough and transported fault-propagation and detachment folds (e.g., Butler, 1982a; Suppe, 1983; Jamison, 1987; Thomas, 1990; Apotria *et al*., 1992; Cook & Thomas, 2009; Poblet & Lisle, 2011). This may provoke additional ramps or more complex cross-strike discontinuity phenomena whilst trying to overcome the obstacle through processes such as vertical-axial rotation (e.g., Ballabio-Barzio Transverse Zone, Southern Alps; Schönborn, 1992).

Abrupt along-strike terminations of structure along footwall ramp intersections or pre-thrust template irregularities are commonly expressed through the creation of structures such as duplexes, antiformal stacks, and geological windows (e.g., Dahlstrom, 1970; Boyer & Elliott, 1982; Mitra, 1986; McClay, 1992; DeCelles *et al*., 2001; Figure 2.13). Well documented examples of these three phenomena produced along frontal and lateral ramp intersections are identified within the:

- Birmingham Graben along the Helena and Pell City faults, Rising Fawn and Anniston transverse zones respectively (e.g., Jacksonville, Fort McClellan and Ballplay windows; Rich, 1992; Thomas, 2001; Thomas & Bayona, 2002; 2005)
- Charleston Transverse Zone, Wyoming-Idaho / Sevier thrust belts (e.g., Grubbs & Van der Voo, 1976; Schwartz & Van der Voo, 1984; Eldridge & Van der Voo, 1988; Montgomery, 1993; Paulsen & Marshak, 1997; 1998)
- Central Andes, Chile along pre-thrust basement highs (e.g., Mouthereau *et al*., 2002; Mescua *et al*., 2010).

Development of these structures will also deflect thrust propagation further during their development, and / or cause along-strike deflections after-thrusting and during culmination development (e.g., Droighinn Anticlinal stack and Breabag Dome, Breabag Stronchrubie system, Traligill Transverse Zone, Assynt Culmination; Krabbendam & Leslie, 2010).

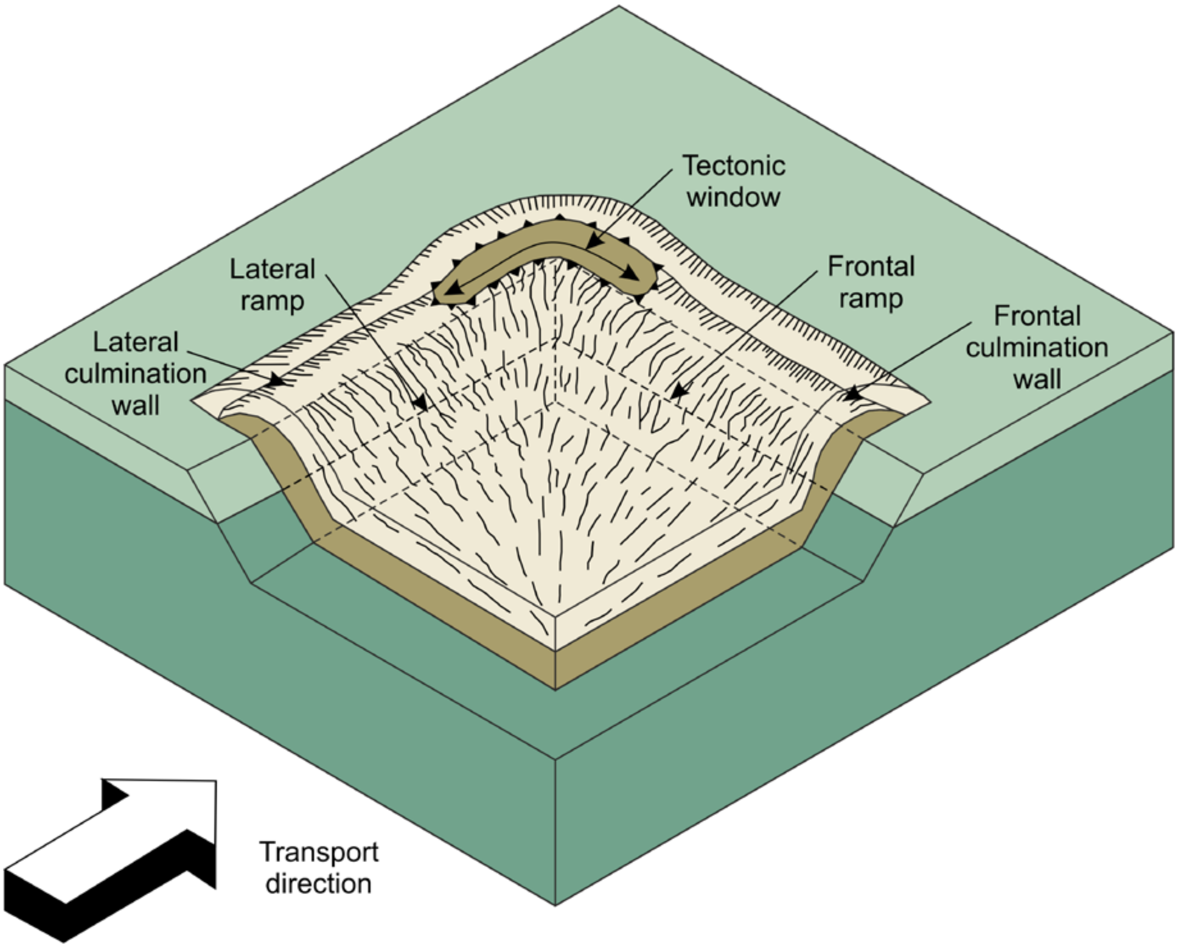


Figure 2.13: Cross-strike discontinuity phenomena produced at the intersection of a frontal/ lateral ramp including, geological windows and hanging-wall folding along frontal/lateral ramp intersection (e.g., frontal/lateral culmination walls) (Adapted after Pohn, 1998).

2.3.2.1. <u>Culmination development</u>

Within this thesis, the concept of a cross-strike discontinuity related to transport-transverse structures, such as lateral ramps, is expanded beyond the original definition of Thomas (1990) to encompass a zone of structural disruption (i.e., faulting, folding, and possible intense fracturing) where décollements change stratigraphical level along structural strike. It is therefore appropriate to also include culmination walls within this classification.

Movement of a thrust sheet over a corrugated autochthonous surface incorporating frontal, lateral and oblique ramps generates flat-topped anticlines and domes with four way closure called structural culminations. The fold limbs are termed culmination walls (e.g., Dahlstrom, 1970; Butler, 1982a; McClay, 1992; Figure 2.13; 2.14). Geometrically similar to thrust ramps; frontal, lateral and oblique culmination walls are developed over their transport-respective ramps during thrust translation (McClay, 1992; Figure 2.13; 2.14).

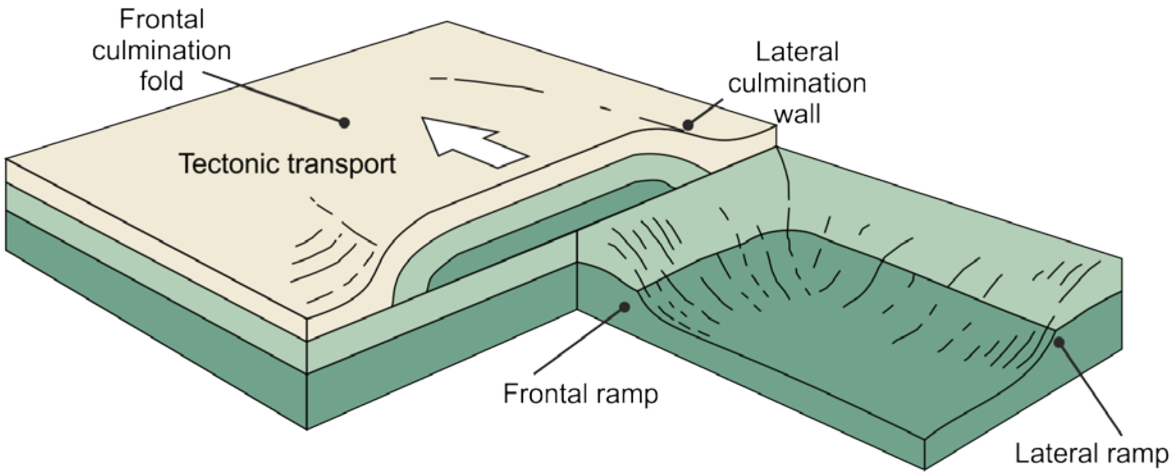


Figure 2.14: Block diagram illustrating the geometry of frontal and lateral ramps with resulting hanging-wall culmination wall fold geometries (Adapted after Schirmer, 1988; Frizon de Lamotte *et al.,* 1991)

Frequently, a culmination in a thrust surface is produced after thrusts are emplaced producing deflected map-view thrust traces. This folding could, in principle run from top to bottom through the entire cross-section including the basement (Boyer & Elliott, 1982). However, balanced cross-sections and seismic exploration reveal that folding itself is a consequence of thrust processes, such as internal bulging along duplexes and / or post-thrust folding restricted to cover rocks above the basal sole / floor thrust (i.e., the lowermost thrust common to a thrust system; Dennis, 1967; Boyer & Elliott, 1982; Figure 2.15). Although the basal sole thrust is unfolded, it is not necessarily smooth; in fact it usually shows lateral and frontal ramps that create the overlying folds and culminations (Butler, 1982a; Figure 2.15).

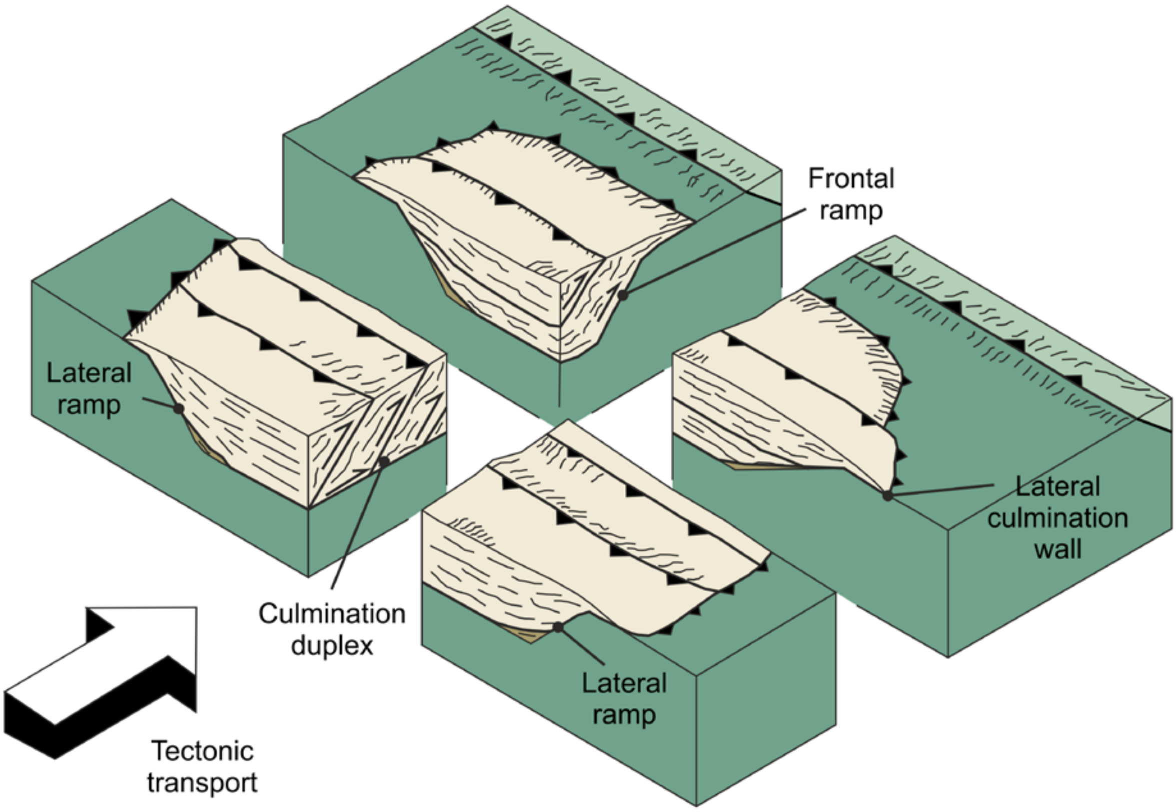


Figure 2.15: Sliced culmination exposed by erosion within a geological window, formed by internal bulging either as a result of new thrust development along internal duplexes and/or post-thrust folding along a frontal ramp and a lateral ramp pair, creating lateral/frontal culmination walls above respective ramps. (Adapted after Pohn, 1998).

Culminations are common within fold-thrust belts including the:

- Alps (e.g., Pfiffner, 1985; DeCelles *et al*., 1995; Schönborn, 1992)
- Appalachians (e.g., Boyer & Elliott, 1982; Brewer, 2004; Cook, 2010)
- Himalayas (e.g., Schelling, 1992; Srivastava & Mitra, 1994 *in* DeCelles *et al*., 1995)
- Pyrenees (e.g., Munoz, 1992 *in* DeCelles *et al*., 1995)
- Canadian Rockies (e.g., Limestone Mountain Culmination; Bégin & Spratt, 2002)

- Moine Thrust Zone (e.g., Assynt, Cassley and Achnashellach culminations; Elliott & Johnson, 1980; Butler *et al*., 2007; Krabbendam & Leslie, 2010; Leslie *et al*., 2010).

Culminations develop on varying scales from small-scale localised developments, such as the Canyon Range Culmination, Sevier fold-thrust belt, Utah, where the Canyon Range Thrust was folded by the growth of a footwall antiformal stack exposed within a truncated geological window (similar to Figure 2.15; DeCelles *et al*., 1995), to large-scale developments up to twenty kilometres wide (e.g., Assynt Culmination, Moine Thrust Zone, Northwest Highlands, Scotland).

In its simplest form, culminations are produced by a duplex with one frontal and two lateral ramps as a result of dissimilar initial fault trajectories, changes in stratigraphical thickness, or variable contraction within the thrust sheet undergoing deformation (Boyer & Elliott, 1982). Pohn (1998), proposed four lateral ramp / culmination models for varying culmination development styles (Figure 2.16). These included:

1. Parallel-sided ramps connected to a horizontal décollement (Figure 2.15, 2.16a),
2. Parallel-sided ramps connected to a rising décollement (Figure 2.16b),
3. Convergent-sided ramps connected to a horizontal décollement (Figure 2.16c)
4. Convergent-sided ramps connecting to a rising décollement (Figure 2.16d)

Each of these geometries, with the exception of the first, produces a smaller cross-sectional area at its distal margin. Therefore, the last three geometries (i.e., Figure 2.16b-d) require lateral spill-over points, or along-strike movement, of compressed material. None of these last three geometries requires a frontal ramp to initiate movement along-strike. Lateral movement within these models is produced solely by volumetric construction within the transport direction (Pohn, 1998).

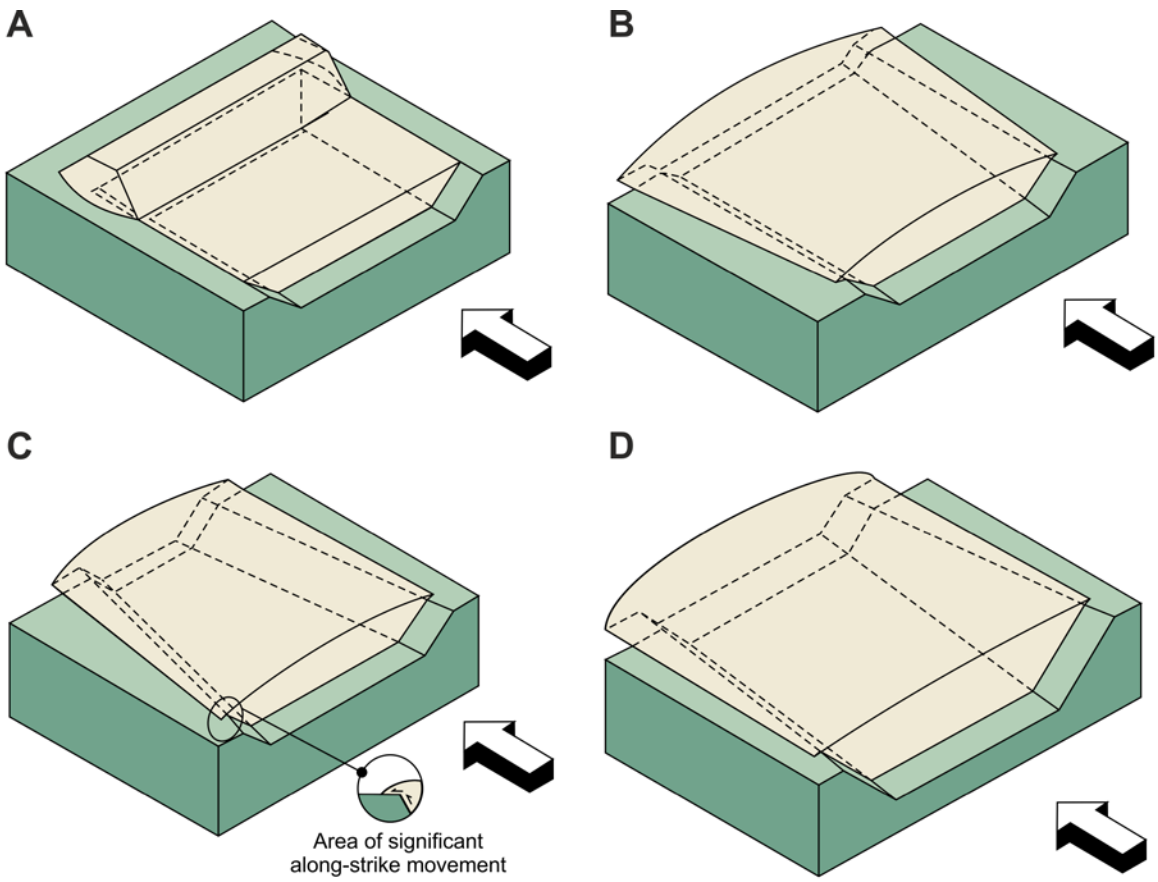


Figure 2.16: Simplified lateral ramp block diagrams depicting four basic geometric configurations for culmination development. Arrows show relative sense of movement on fault. **(A)** Parallel-sided lateral ramp connected to a horizontal décollement. **(B)** Parallel-sided lateral ramp connected to a rising décollement. **(C)** Convergent-sided lateral ramp connected to a horizontal décollement. **(D)** Convergent-sided lateral ramp connected to a rising décollement. (Adapted after Pohn, 1998).

Culminations produced by parallel-sided ramps connected to a horizontal décollement may produce along-strike movement if the angle of lateral ramp is shallower than the dip of an accompanying frontal ramp or if material along-strike is more compressible than material along dip (Pohn, 1998). Convergent-sided ramps connecting either horizontal or rising décollements produce a paradox in terminology. Both geometries are more correctly considered to be oblique ramps rather than lateral ramps at depth. However, surface manifestations of these oblique ramps show the geometry of true lateral ramps (Pohn, 1998). Therefore, in order to define lateral and oblique ramps at depth, benefits of three-dimensional seismic reflection data profiles are required to determine both surface and subsurface profiles.

2.3.2.2. Vertical-axial thrust sheet rotations

Although a dominant orientation of tectonic transport prevails, in detail the sense of motion of each thrust sheet may vary in its orientation spatially and / or through time (Poblet & Lisle, 2011). A growing body of evidence suggests that rotations about vertical axes are a common element of fold-thrust belt and cross-strike discontinuity evolution. These rotational deformations have important consequences for the geometry and kinematics of thrusting (Allerton, 1998). Vertical-axial rotations occur within both large- and small-scale processes including:

- oroclinal bending (e.g., Andes, Appalachians, Carpathians and the Cantabrian Arc, northern Spain; Allerton, 1998; Parés *et al*., 2004; Tull & Holm, 2005; Cook & Thomas, 2009; Cook, 2010 and references therein),
- formation of antaxes and salients (e.g., Himalayas, Rockies and Western Tauric thrust belt; Schwartz & Van der Voo, 1984; Treloar *et al*., 1992; Kissel *et al*., 1993),
- strike-slip fault system developments (e.g., Tien Shan Thrust Belt and California; Luyendyk, 1991; Thomas *et al*., 1993),
- rotational thrust systems (e.g., Betic Cordillera, southern Spain and Sicily; Osete *et al*., 1989; Channell *et al*., 1990; Platzman, 1992; Allerton *et al*., 1993).

Any movement of a body on the Earth's surface can be described as a rotation about a pole (Allerton, 1998). On a local scale, translation of a thrust sheet is equivalent to a far-field rotation, whilst local rotation of the sheet is equivalent to a near-field rotation (Apotria, 1995; Allerton, 1998). As a thrust sheet moves over a corrugated autochthonous surface, thrust sheet rotations occur as a consequence of the geometry of the sheet with respect to applied stresses, abrupt differential slip changes along detachment level, strong to weak lithological changes, weight of overburden, gradients in depth to basement, or alternatively, from differential resistances on the base and sides of the sheet creating cross-strike discontinuity phenomena along-strike (Apotria *et al*., 1992; Wilkerson *et al*., 1992; Allerton, 1998; Muttoni *et al*., 1998; Thomas, 2001; Bayona *et al*., 2003; Cook, 2010). However, unlike culmination development, where culmination walls develop over their respective footwall parental structures, cross-strike discontinuity phenomena produced by vertical-axial rotations of thrust sheets may be no longer positioned over their parental structure. Continued thrust sheet rotations reposition cross-strike discontinuity phenomena obliquely to parental structures (e.g., Pell City Thrust Sheet, Harpersville Transverse Zone, Alabama, USA; Tull & Holm, 2005; Cook & Thomas, 2009).

Simplest expression of rotation within thrust sheets can be identified by along-strike differential shortening, which is not accommodated by lateral structures such as transverse faults. Bates (1989) was one of the first to recognise the importance of differential shortening as a mechanism for generating large rotations within thrust belts within the eastern Pyrenees, identifying that local differential rotation between thrust sheets were accommodated by along-strike changes in the amount of shortening on frontal and laterally bounding thrusts and folds (Figure 2.17a). Non-cylindrical folding, conical folds and changes from open to isoclinal folding along the rotation axis are an expression of thrust sheet rotations in map-view (Allerton, 1998; Pastor-Galan *et al*., 2012). Bates (1989) further identified that rotating thrust sheets cannot extend indefinitely along-strike because differential shortening would also increase indefinitely. Therefore thrust sheets are often bounded laterally by strike-slip faults orthogonal to strike (i.e., transverse faults), the sense of slip on which will evolve during rotation.

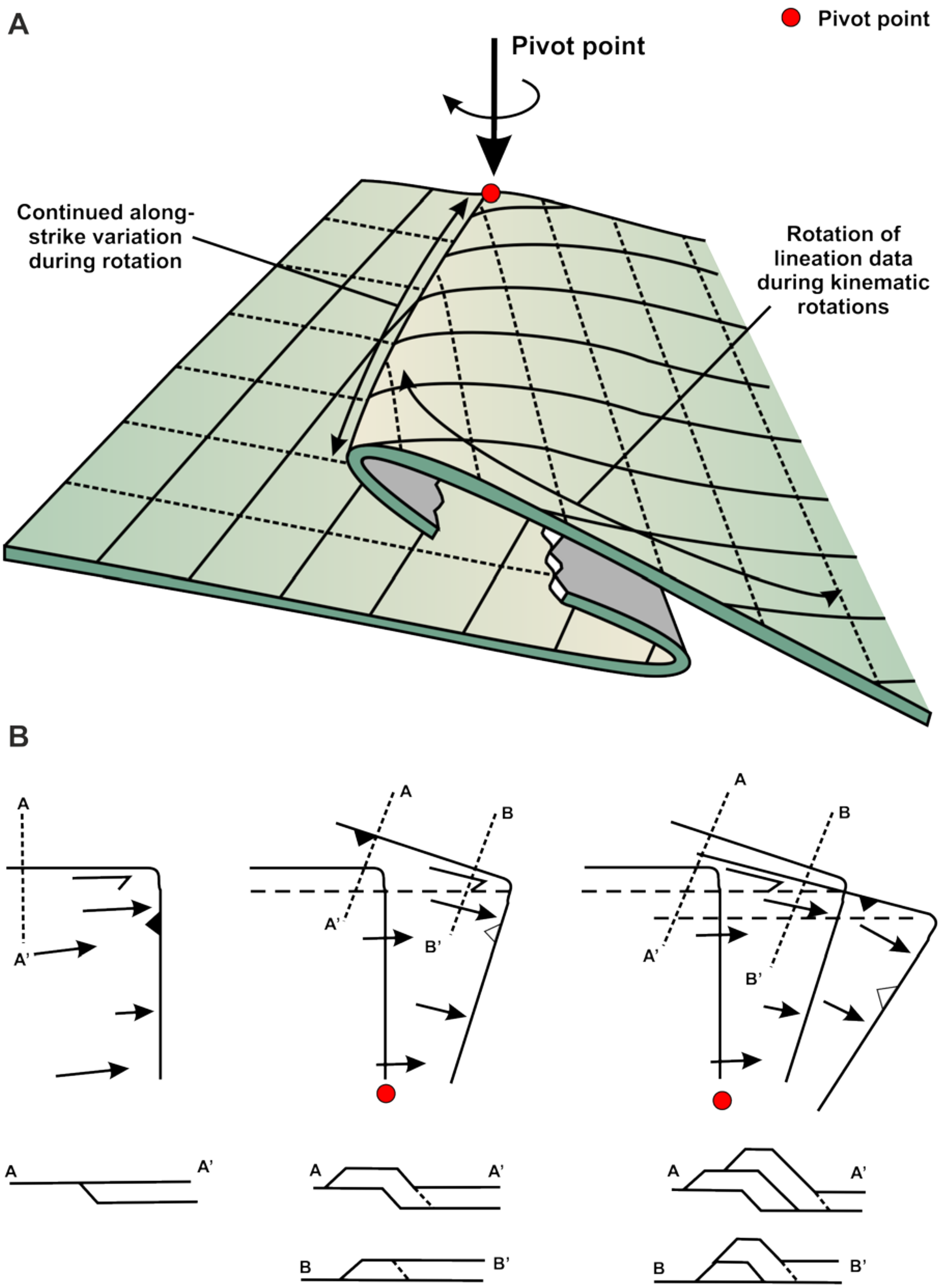


Figure 2.17: (A) Simplified diagram illustrating rotation associated with differential shortening related to folding and thrusting or buttressing against a transverse fault/sidewall ramp producing a sidewall duplex. **(B)** Development of sidewall duplexes by rotation along a sidewall ramp. Plan view, with section, the position of which is indicated by the fine-dashed line. coarser-dashed line represents the position of an incipient fault. Thrusting over the frontal ramp is accommodated by strike-slip with a component of shortening, on the lateral ramp. As the sheet moves and rotates, it rides obliquely over the lateral ramp, and the process repeats itself, gradually accreting a hanging-wall duplex at the lateral ramp (Adapted after Allerton, 1998).

Development of transverse faults and / or sidewall ramps may initiate essentially parallel to the transport direction. In non-rotational thrusting, this would essentially continue to act with a dominantly strike-slip sense of movement and remain stable (Allerton. 1998). In rotational thrusting, direction of thrust-sheet motion over a transverse fault or sidewall would evolve to a progressively greater component of shortening. This may continue, so that the hanging-wall part of the transverse fault presents itself as a progressively more frontal thrust, or alternatively, it may fail along the footwall ramp to provide a new fault with a strike-slip movement sense, which may again evolve to progressively greater thrust components which may again fail (Allerton, 1998; Figure 2.17b). This provides a mechanism for the development of cross-strike discontinuity phenomena, such as sidewall duplexes within the hanging-wall or footwall, examples of which can be identified within the Birmingham Graben system, southern Appalachian Thrust Belt, Alabama, USA and Papua New Guinea fold-thrust belt (Apotria *et al*., 1992; Weiler & Coe, 1997; Allerton, 1998; Graham, 1999; Thomas, 2001).

Apotria (1990; 1995) and Apotria *et al*., (1992) supported these observations, identifying that vertical-axial rotations are common along oblique and lateral ramp intersections associated with the production of displacement gradients along oblique ramps, hanging-wall plunging folds, and transverse faults, with the greatest amounts of rotation occurring at the hanging-wall lateral ramp cut-off (i.e., structures directly near to, or overlying the ramp; Apotria *et al*., 1992).

Within rotational thrust systems, thrust propagation over frontal, lateral and oblique ramps promotes further thrust sheet rotations as a result of piggy-back rotations (e.g., the Canadian Rockies; Boyer & Elliott, 1982). Boyer & Elliott (1982) and Bates (1989) identified that large amounts of rotation can be accumulated by the accretion and rotation of progressive sheets in a thrust sequence. Thrust sheets carried on the back of rotating thrust sheets would themselves be rotated creating cross-strike discontinuities (Bates, 1989; Allerton, 1998; Figure 2.18). Within the Canadian Rockies, thrust sheets within the footwall were observed to be largely detached from both the foreland and hinterland, and would be free to move independently with respect to both. However, for rotation to occur within a deforming zone, more than one fault must be active for detachment separate from both the hinterland and foreland (Bates, 1989; Allerton, 1998; Figure 2.18). Differential rotation may therefore provide important evidence for thrust propagation directions in the absence of other structural information (Boyer & Elliott, 1982).

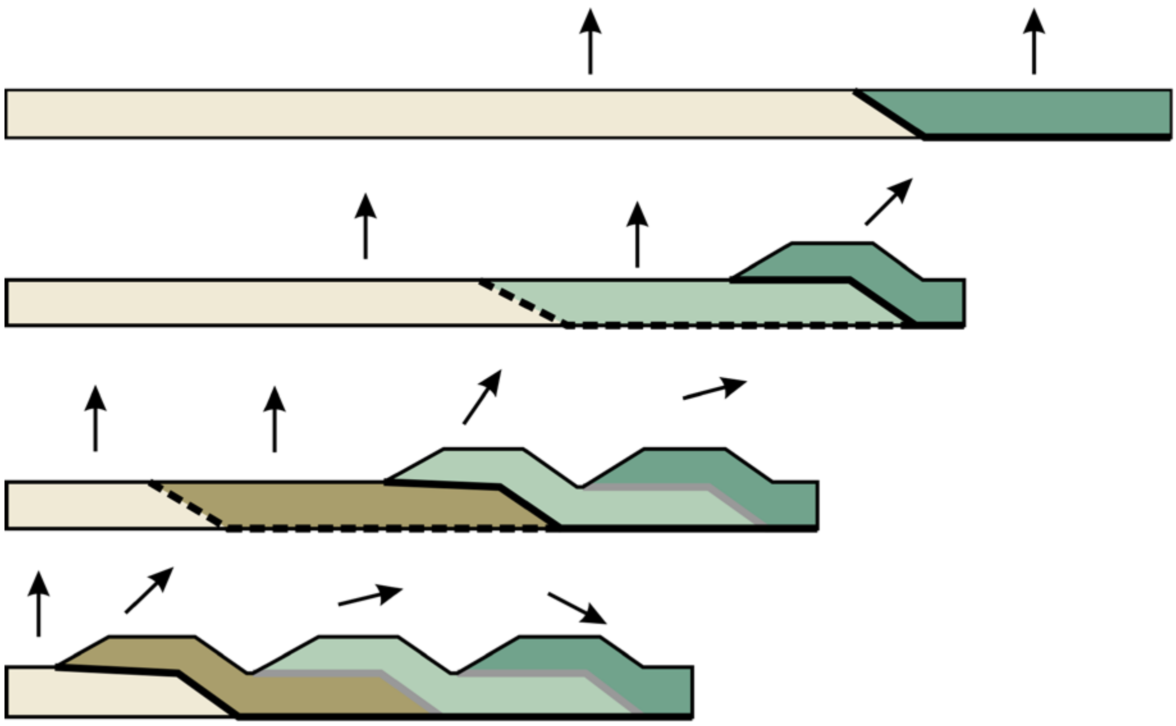


Figure 2.18: Accumulation of large differential rotations by progressive rotation on individual sheets as a result of piggy-back rotation. Black arrows indicate rotations about vertical axes. Black solid lines: active thrust surfaces. Black dashed lines: incipient thrust surfaces. Grey solid lines: represent inactive thrusts. (Adapted after Allerton, 1998).

Within large-scale systems, McKenzie & Jackson (1983) and Allerton *et al*., (1993), identified that thrust ramps initiated oblique to palaeo-margins or transport direction, rotate into parallelism with the palaeo-margin or transport direction, creating along-strike structural variations. This process will progressively favour partitioning of deformation into orthogonal shortening and parallel strike-slip; a stable condition which may inhibit further rotation (Allerton, 1998). Further large-scale examples of vertical-axial rotations are identified within the Charleston Transverse Zone, Sevier fold-thrust belt, Utah and the central / southern Appalachian transition zone within the Johnson City region, Tennessee, where clockwise and / or counter-clockwise fault block rotations are identified (Pohn, 1998; Paulsen & Marshak, 1998; Tull & Holm, 2005; Figure 2.19).

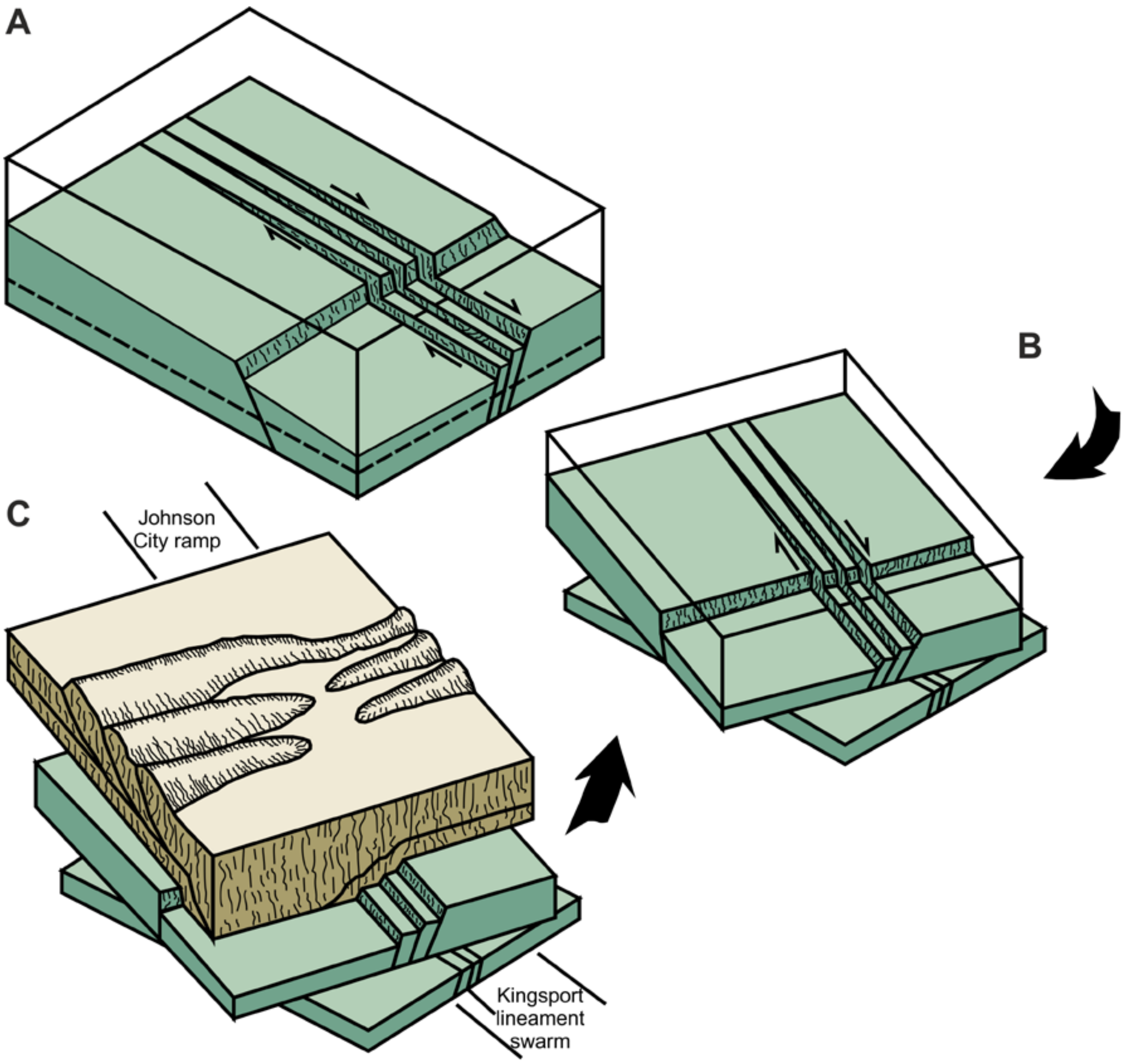


Figure 2.19: Block diagrams illustrating rotation and translation of the southern Appalachians around the central Appalachians in the Johnson City, Tennessee region. **(A)** Strike-slip-faulted basement with future décollement surface shown by heavy dashed line. **(B)** Rotation of basement block on décollement surface. **(C)** Translation of the basement and cover sequence. Plunging folds developed over the lateral ramp that is, in turn, formed over strike-slip faults. (Adapted after Pohn, 1998).

Within the Johnson City transition zone, basement-rooted strike-slip faults, forming the Kingsport lineament swarm at the surface within the Blue Ridge or Piedmont province, are rotated before basement and cover strata are translated over lateral / oblique ramps forming cross-strike structural discontinuity phenomena (i.e., plunging folds) within the Valley and Ridge province as a result of differential erosion along regional décollement levels (Pohn, 1998; Figure 2.19).

Invariably, production of map-view cross-strike discontinuity phenomena such as, duplexes and antiformal stacks, geological windows, structural culminations and deflected thrusts and / or folds as a result of thrust propagation and processes such as vertical-axial rotations, primarily hinges on whether cross-strike discontinuity phenomena are the product of one primary deformation phase or of multiple episodes of deformation, including at least two thrust directions, imposing differing stress fields upon pre-existing structures (Cook, 2010). If deformation occurred in more than one phase, complex interference structures would be produced creating along-strike structural discontinuity phenomena. Conversely, if one deformation phase occurred, than an altogether different yet no less complex set of structures would result (Cook, 2010).

2.4. Summary

Over the last fifty years, research has documented that abrupt lateral changes in fold-thrust geometries occur in many mountain-building fold-thrust belts globally with profound architectural complexities segmenting the orogenic front. Such along-strike variations are common as a result of the mechanical difficulty of displacing large volumes of rock during allochthon formation. Along-strike variation in fold-thrust architecture may be randomly distributed within the allochthon; however, many are aligned into kilometre-wide zones termed cross-strike structural discontinuities (CSDs), representing the surface expression of transverse zones at depth, encompassing various cross-strike linkages and cross-strike discontinuity phenomena.

Controls on the locations of cross-strike discontinuity phenomena, cross-strike linkages and transverse zones are complex and occur over many scales. In many cases, causative structures of lateral changes are often concealed by distal parts of the thrust belt or by foreland basin strata. However, this chapter highlights that cross-strike discontinuity / transverse zone formation is critically dependant on the relationship between pre-thrust template composition and subsequent thrust translation during allochthon formation. Cross-strike discontinuities are commonly caused by kinematic responses to irregularities generated across pre-existing, sometimes reactivated, pre-, syn- and / or post-depositional basement faults, along-strike variations in mechanical stratigraphy / lithofacies in the deforming sedimentary wedge, or combinations of the two within the pre-thrust template. Such along-strike variations in the pre-thrust template determine the location of cross-strike linkages including, lateral and / or oblique ramps, displacement-transfer zones and transverse faults.

The role of thrust translation critically determines the spectrum of cross-strike discontinuity phenomena produced. Pre-existing basement structures may be reactivated during early pulses of allochthon development depending on orientation to the imposed stress field. Conversely, where transport is oblique to pre-existing structures or along-strike rheological changes, varying map-view cross-strike discontinuity phenomena are created including duplexes, antiformal stacks, geological windows and various fold-thrust geometries as a result of along-strike buttressing, transpression, transtension and thrust sheet vertical-axial rotations.

Development of map-view cross-strike discontinuity phenomena is also dependent on whether map-view representations occur as a result of one primary deformation phase or multiple deformation phases. Within multiple deformation phases, complex interference structures are produced through reactivations of previous inheritance structures, development of new structures cross-cutting previous structures overprinting earlier structures or deflecting previous structures during culmination development or rotation of thrust sheets during forelandward and out-of-sequence thrust propagations. Such secondary-phase deformations would also reposition map-view cross-strike discontinuities obliquely and farther away from parental structures compared to structures produced by single deformation events.

Identification of map-view representations of subsurface cross-strike discontinuities and their potential controls is therefore vital for utilisation within the Moine and Cantabrian thrust belts. Previous examples of cross-strike discontinuities and transverse zones studies within the research literature allow surface expressions of subsurface irregularities within many fold-thrust belts to be analysed and compared, thus allowing comparisons to be drawn for structural developments along-strike within the Moine and Cantabrian thrust belts within this research.

Chapter Three:

Architectural analysis of Cross-strike Discontinuities: new identification and classification methodologies

Over the last fifty years, various criteria and techniques have been implemented for the identification and interpretation of cross-strike discontinuities and transverse zones. Within this chapter, existing techniques for cross-strike discontinuity / transverse zone identification are reviewed. A new methodology is then presented that places particular emphasis on the identification of cross-strike linkages within transverse zones. The methodology is tested within the Appalachians Thrust Belt. A work-flow is then presented for implementation within the Moine and Cantabrian thrust belts.

3.1. Cross-strike discontinuity / transverse zone identification techniques: A review

This section reviews pertinent cross-strike discontinuity identification techniques developed over the last fifty years. During this period, the numerous techniques implemented include:

- Deep structural analyses on regional scales (e.g., Keller & Hatcher, 1999)
- Structural contour mapping, seismic analyses, Bouguer gravity and aeromagnetic anomaly mapping and well-log data interpretations (e.g., Thomas, 1985; Keller & Hatcher, 1999; Bégin & Spratt, 2002; Brown *et al*., 2008; Pashin *et al*., 2010),
- Facies analyses and provenance mapping, palinspastic reconstructions and isopach analyses (e.g., Bayona *et al*., 2003; Brewer, 2004; Tull & Holm, 2005; Bayona & Thomas, 2006; Cook, 2010; Aschoff *et al*., 2011),
- Stratigraphical separation diagram construction along the hanging-walls of individual thrust map-traces to identify lateral ramps and along-strike

stratigraphical correlation panels (e.g., Woodward, 1987b; DeCelles & Coogan, 2006; Kwon & Mitra, 2006; Turner *et al*., 2010),

- Detailed mapping of areas displaying cross-strike discontinuities incorporating field data collections of fault and fold geometries and kinematic analyses such as fault movements (slickenlines), vein and cleavage orientations and cross-cutting relationship analyses (e.g., Paulsen & Marshak, 1998; Tull & Holm, 2005; Kwon & Mitra, 2006; Yassaghi & Madanipour, 2008; Cook, 2010),

- Construction of transport-parallel and transport-lateral cross-sections and along-strike pseudo-three-dimensional analyses (e.g., Brewer, 2004; Kwon & Mitra, 2006; Leslie *et al*., 2010; 2012; 2013),

- Analogue modelling in two and three dimensions to determine along-strike tapering and transverse zone development (e.g., Malavieille *et al*., 1991; Mouthereau *et al*., 2002; Bigi *et al*., 2009).

Individual techniques are summarised into three main groups determined by their similar end results. These include:

- <u>Regional-scale structural and stratigraphical analyses</u> integrating seismic data analyses, Bouguer gravity, aeromagnetic anomaly and structural contour mapping, sedimentary facies analyses and provenance mapping, along-strike sedimentary thickness identifications utilising well-logs, isopach interpretations and construction of stratigraphical correlation panels and / or stratigraphical separation diagrams.

- <u>Detailed regional and local-scale field studies</u> combining the analysis and / or validation of previous geological maps and data sets, acquisition of new geometrical and kinematic data, construction and / or palinspastic restoration of new transport-parallel and transport-lateral cross-sections.

- Modelling techniques combining two- and three-dimensional approaches utilising digital and analogue methods.

Principles, implications, advantages and disadvantages relevant to transverse zone identifications are discussed in the following subsections in greater detail.

3.1.1. Regional-scale structural and stratigraphical analyses

Integrated studies of structural and stratigraphical techniques have been used in many fold-thrust belts to determine depth to autochthonous basement and internal geometry and composition of overlying allochthonous cover strata (Thomas, 1985; Keller & Hatcher, 1999). Applications of these techniques have focussed primarily on gaining a greater understanding of both the lithospheric development and the implications for hydrocarbon exploration over a variety of spatial scales (e.g., Pérez-Estaún *et al*., 1997; Bégin & Spratt, 2002; Brown *et al*., 2008; Goffey *et al*., 2010).

Within cross-strike discontinuity studies, these techniques have been used to determine the impacts of pre-thrust templates on subsequent fold-thrust belt development (e.g., Berger, 2001). Commonly, research has focussed on identification of fault-bounded irregularities within the basement, and the extent to which bounding faults have pre-, syn- and / or post-depositional reactivations, resulting in along-strike variations in depth of cover strata. Such along-strike variations have implications for along-strike changes in décollement-host strata, and focussed compartmentalisation within any subsequent fold-thrust belt (Thomas, 1990; Berger, 2001).

3.1.1.1. Bouguer gravity and aeromagnetic anomaly mapping

In geodesy and geophysics, the Bouguer anomaly is a gravity anomaly (i.e., the difference between the observed acceleration of a planet's gravity and a value predicted from a model), corrected for the height at which it is measured and the attraction of terrain (Lowrie, 2004). A location with a positive anomaly exhibits more gravity than predicted, while negative anomalies exhibit lower values than predicted (Sideris & Forsberg, 1991; Lowrie, 2004; Figure 3.1a). To understand the nature of the gravity anomaly in the subsurface, a number of corrections must be made to the measured gravity value including, theoretical gravity, Free-Air corrections and Bouguer corrections (e.g., Sideris & Forsberg, 1991; Lowrie, 2004; Burger *et al*., 2006; Hofmann-Wellenhof & Moritz, 2006).

Within regional aeromagnetic surveys, towed magnetometers record small intensity variations of the ambient magnetic field due to temporal effects of varying solar winds and spatial variations in the Earth's magnetic field (Burger *et al*., 2006). By subtracting solar and regional effects, resulting aeromagnetic maps demonstrate spatial distribution and relative abundance of magnetic minerals (Burger *et al*., 2006). As different rock types differ in their content of magnetic minerals, magnetic anomaly maps allow visualisations of subsurface geological structures, particularly spatial geometries of rock bodies and the presence of faults and folds (Figure 3.1b). Aeromagnetic anomaly maps were once presented as contour plots, but are now more commonly presented as coloured pseudo-topography images (Brown *et al*., 2008; Figure 3.1b).

Bouguer gravity and aeromagnetic anomaly identifications have been applied within several fold-thrust belts to determine major subsurface features including; the Jura Mountains, Germany / Switzerland; Ouachita Mountains, Oklahoma, USA; fold-thrust belt regions of the North Slope of Alaska; and the Uralide Mountains, Russia (e.g., Berger,

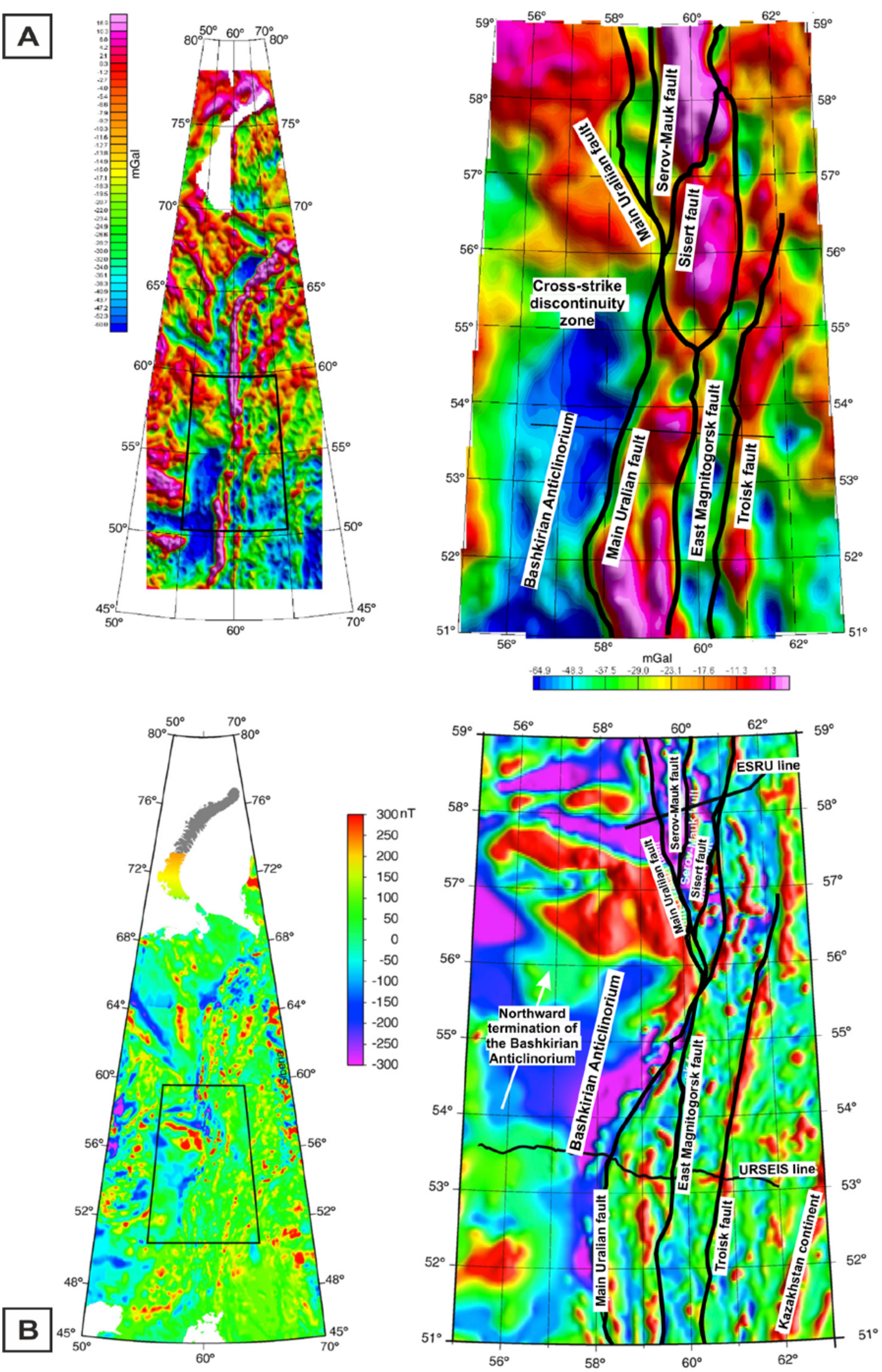


Figure 3.1: (A) Bouguer gravity and **(B)** aeromagnetic anomaly maps of the Uralides with particular focus along the main faults within the southern and middle Urals. Both surveys indicate along-strike changes in depth to basement and fault interactions as a result of northward thinning of stratigraphical cover, termination of the Bashkirian Anticlinorium and thickening basement (Adapted after Brown *et al.*, 2008).

2001; Brown *et al*., 2008 and references therein; Figure 3.1). These techniques have also been utilised within the Moine and Cantabrian thrust belts (e.g., British Geological Survey, 1997; 1998; Pedreira *et al*., 2010; Gómez-Ortiz *et al*., 2011 and references therein).

Within the southern Uralide fold-thrust belt, Brown *et al*., (2008) used gravity and aeromagnetic data to constrain the extent of several important structures mapped at the surface and viewed within seismic reflection data (e.g., development of the Main Uralian Fault northwards into the Uralian, Serov-Mauk and Sisert faults; Figure 3.1). Development of this northwards branching is a result of northwards thinning of cover strata at the northern termination of the Bashkirian Anticlinorium and a northward thickening of basement material causing greater fault divergence along-strike (Pérez-Estaún *et al*., 1997). Another good example of the use of these techniques within cross-strike discontinuity research can be identified within the Cassley Culmination located within the hinterland of the Assynt Culmination of the Moine Thrust Belt (e.g., Leslie *et al*., 2010). Gravity data suggest that the Oykel Bridge Transverse Zone overlies a step in basement that bounds the south-western edge of the Assynt and Cassley culminations and along which the Oykel Bridge Transverse Zone developed (Leslie *et al*., 2010).

Bouguer gravity and aeromagnetic anomalies are therefore ideal for regional-scale identification of cross-strike discontinuities as they illustrate along-strike variations in different rock densities and faults within the subsurface, which subsequently focus deformation within the allochthonous cover strata. However, finer scale along-strike anomaly studies require greater filtering of data depending on the quality of gravity data coverage, sophistication of software and relative cost. Advantages and disadvantages of these techniques are identified within Table 3.1.

Bouguer gravity and aeromagnetic anomaly mapping	
Advantages	**Disadvantages**
• Varying scales of survey – integration of regional- to continental-scale studies • Very accurate within high density studies – sensitive to height changes of ~3 cm and can therefore be implemented in many studies • Visualisation of subsurface geological structures (e.g., faults and folds) and along-strike changes in depth to basement	• Regional-scale analysis – fine-scale detail requires filtering of the data to identify local anomalies and a non-unique interpretation may be produced • Variable accuracy dependant on quality / density of gravity coverage and sophistication of software • Cost – very expensive and normally only utilised within large-scale regional projects in areas which are of academic and / or economic importance (e.g., hydrocarbon exploration)

Table 3.1: The advantages and disadvantages of Bouguer gravity and aeromagnetic anomaly mapping techniques within cross-strike discontinuity studies

3.1.1.2. Seismic data analyses

Seismic waves are mechanical perturbations that travel in the Earth at a speed governed by the seismic velocity of the medium in which they are travelling (Mooney & Brocher, 1987; Sheriff & Geldart, 1995). When a seismic wave travelling through the Earth encounters an interface between two materials with different acoustic impedances, some of the wave energy will reflect off the interface and some will refract through the interface (Mooney & Brocher, 1987; Sheriff & Geldart, 1995).

Seismic reflection techniques consist of generating seismic waves and measuring time taken for waves to travel from the source, to reflect off an interface and to be detected by an array of receivers at the surface. Identifying travel times from the source to various receivers, and velocity of the seismic waves, allows reconstructions of wave pathways to be established in order to build up a subsurface image (Mooney & Brocher, 1987). Conversely, seismic refraction involves measuring the travel time of the component of seismic energy which travels down to the acoustic interface, is refracted along that interface, and returns to the surface as a head wave along a wave front (Mooney & Brocher, 1987; Sheriff & Geldart, 1995).

Active and passive seismic surveys, including multichannel reflection / refraction profiles (Figure 3.2), teleseismic receiver function (RF) analyses / RF pseudo-migrated sections (Figure 3.3) and P-wave velocity models (Figure 3.4a), have been implemented in many fold-thrust regions (e.g., EUROPROBE; LITHOPROBE; GEODE; URSEIS 95'; and LISPB surveys; Keller & Hatcher, 1999; Brown *et al*., 2007), including the Moine and Cantabrian thrust belts (e.g., MOIST and ESCIN surveys; Smythe *et al*., 1982; Butler & Coward, 1984; Butler, 1986; Coward *et al*., 1989; Gallastegui *et al*., 1997; Pedreira *et al*., 2003; Fernández-Viejo & Gallastegui, 2005; Diaz *et al*., 2009; Fernández-Viejo *et al*., 2009 and references therein). These have been used over various scales to constrain geometries of seismic discontinuities and depth to basement interpretations (Figure 3.2a, 3.2b). Teleseismic receiver function (RF) analyses provide information from teleseismic earthquakes recorded at a three component seismograph. A teleseismic P-wave generates P to S conversions beneath the seismograph which contains information about the distance to the underlying boundary. Deconvolution of the incoming vertical and longitudinal components, removing the source and travel path information, allows the resulting waveform (i.e., the receiver function) to be analysed (Langston, 1979).

Within large-scale cross-strike discontinuity studies, multichannel reflection / refraction profiles, teleseismic receiver function (RF) analyses and RF pseudo-migrated seismic data analyses have been used to identify along-strike changes in depth to décollement-host strata and large-scale along-strike changes in thrust architecture (e.g., ESRU and URSEIS profiles, southern Ural profiles, and ESCIN-1 transects, Cantabrian thrust belt, northern Spain; Brown *et al*., 2008; Díaz *et al*., 2009; Figure 3.1b; 3.2a; 3.3). Within the

Uralide Mountains a distinct south-to-north change in décollement style is identified along-strike from shallow-dipping décollement reflectors in the south, to steep-dipping reflectors in the north (Figure 3.2a). This has been interpreted as a result of along-strike changes in depth to basement (Pérez-Estaún *et al*., 1997; Brown *et al*., 2008). However, observations at depth are only as good as the interpretation of the operator, and therefore high quality data sets handled by experienced operators are required.

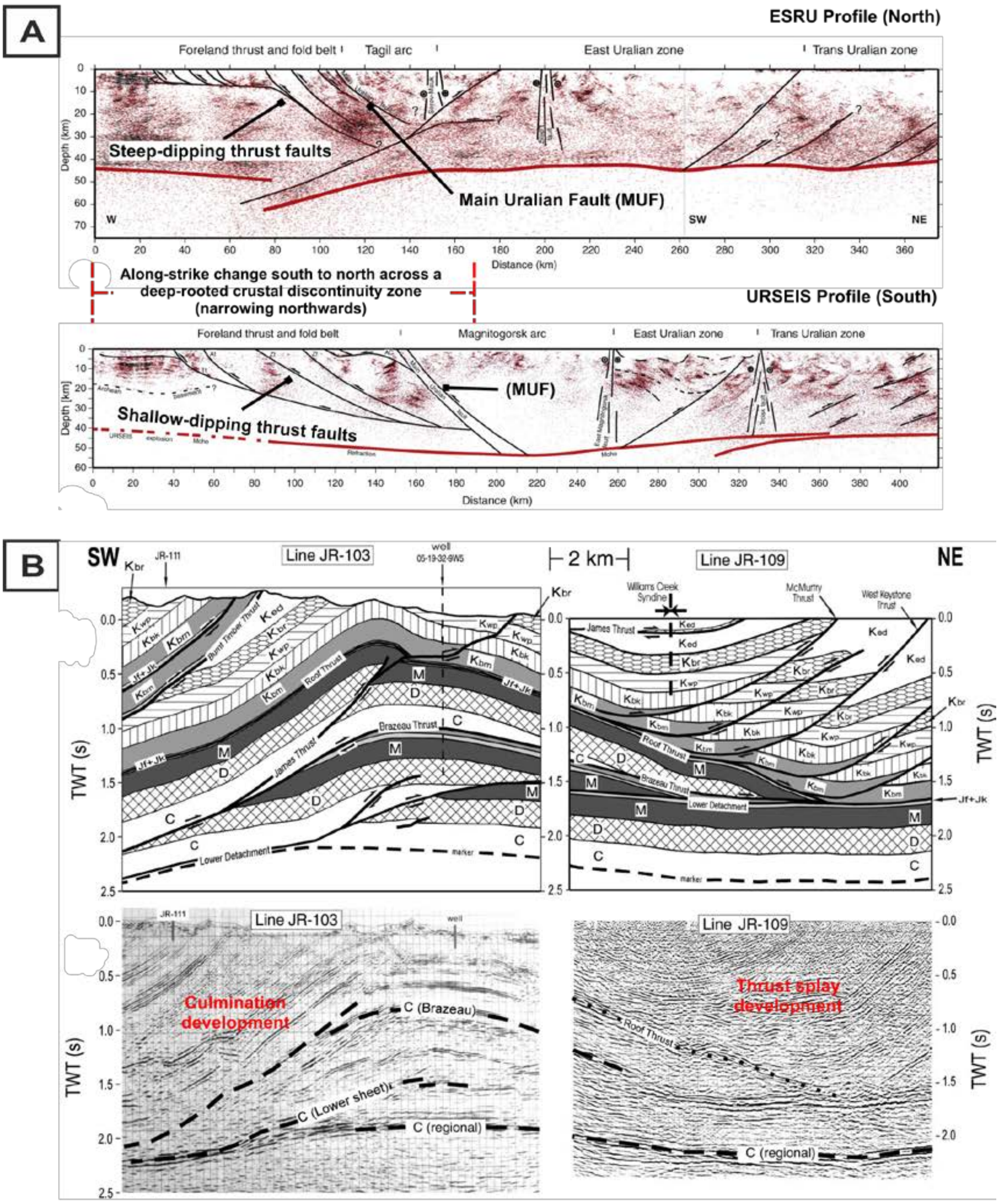


Figure 3.2: Interpreted seismic profile cross-sections over a variety of scales. **(A)** Deep regional-scale (20 km interval) seismic profile analyses within the southern Urals identifying along-strike structural variations from south to north, most notably highlighted by along-strike changes within the Main Uralian Fault (MUF) (adapted after Brown *et al*., 2008). **(B)** Small-scale (2 km interval) interpreted seismic profile analyses within hydrocarbon producing, transverse zone bounded, culminations identifying along-strike structural variations for hydrocarbon seals and potential migration pathways (Bégin & Spratt, 2002).

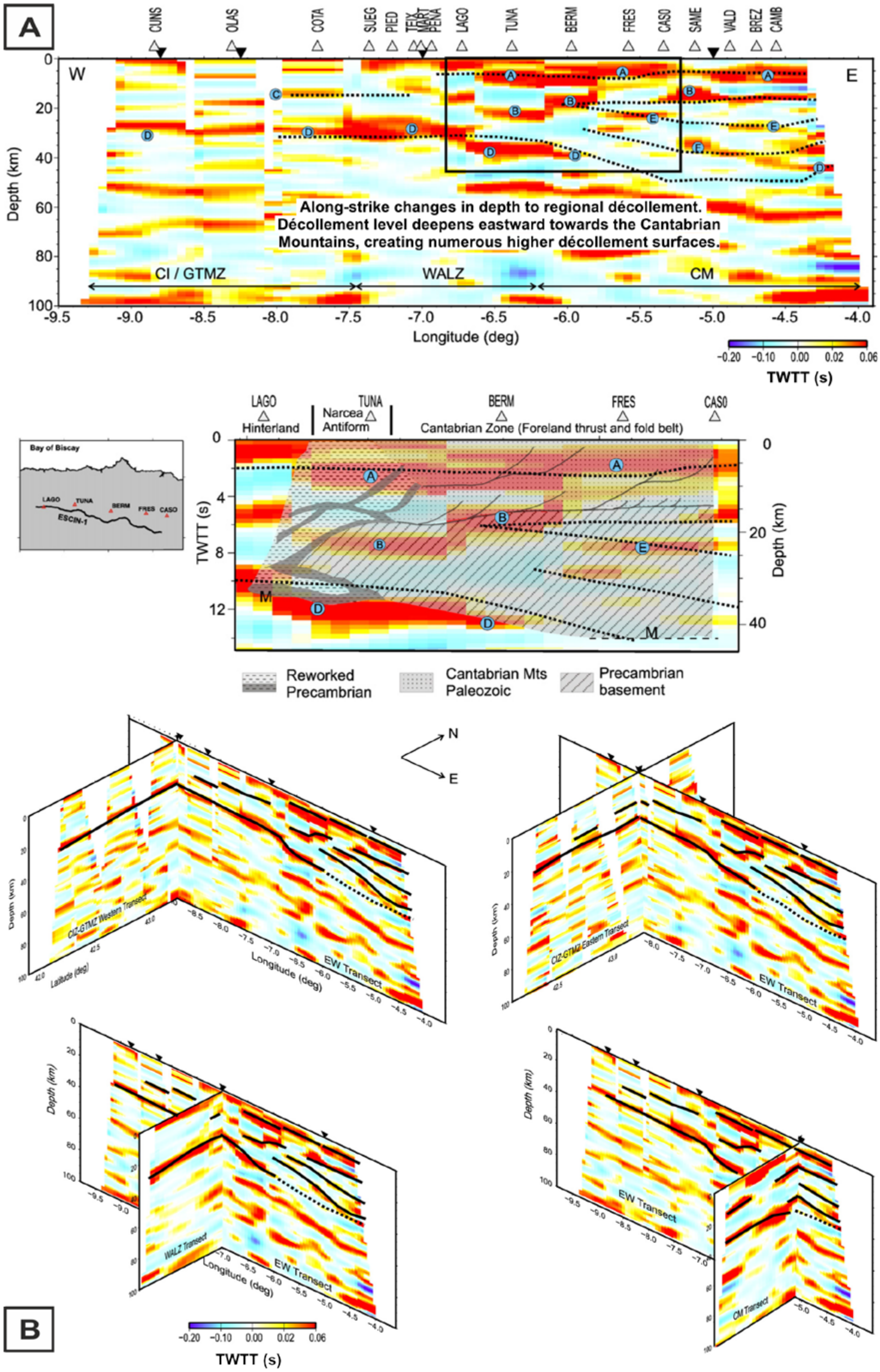


Figure 3.3: (A) Pseudo-migrated crustal sections from RF data (ESCIN-1 E-W transect) within the Cantabrian thrust belt indicating a eastward thickening of cover strata above the regional décollement level. **(B)** Block diagrams of the pseudo-migrated RF transects. Black lines indicate continuous surfaces within the seismic surveys. Pseudo-migrated section analyses allow three-dimentional relationships of décollement levels and styles along-strike to be determined (Díaz *et al.*, 2009). Vertical scale of the of the reflection profile is in seconds (TWTT).

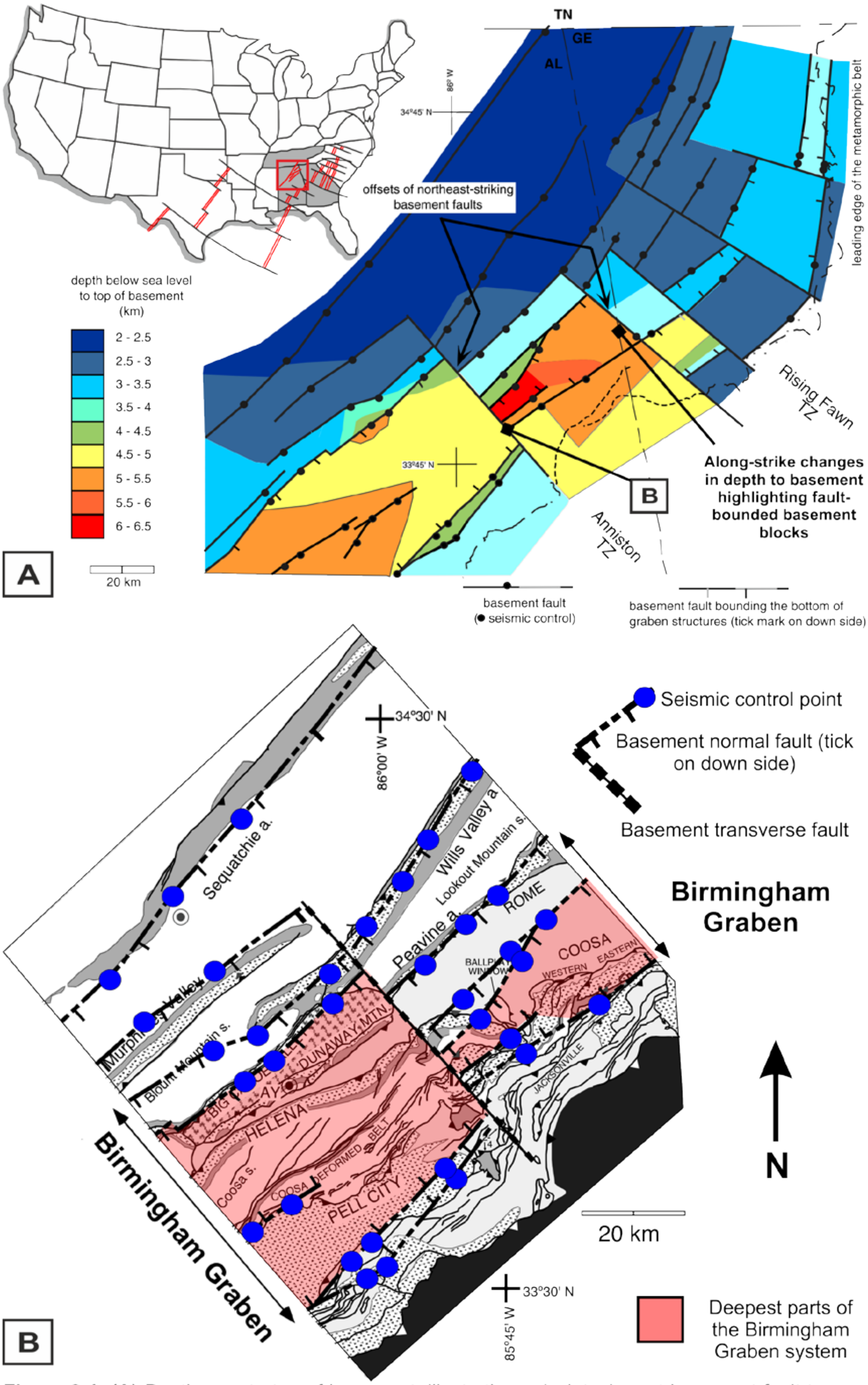


Figure 3.4: (A) Depth map to top of basement, illustrating sub-detachment basement fault traces, Birmingham Graben structural relief, and relationship between transverse basement fault position and transverse zones in the thin-skinned Appalachian foreland thrust belt (Adapted after Bayona *et al.*, 2003). **(B)** Map identifying relationship between present outcrop map-traces and subsurface basement faults interpreted from seismic reflection profiles (Adapted after Thomas & Bayona, 2002)

Conversely, within focussed small-scale cross-strike discontinuity research, seismic refraction techniques have been implemented to constrain subsurface along-strike internal structures, thrust ramp locations and hydrocarbon traps within transverse zone-bounded culminations (e.g., Limestone Mountain Culmination, Canadian Rockies; Bégin & Spratt, 2002, Figure 3.2b). Refraction techniques have been used prevalently within focussed small-scale research of along-strike internal geometries as they provide the most detailed datasets for internal along-strike changes in structure.

Onshore and offshore seismic analyses have also been used to determine migration of deformation fronts and sequences of deformation determinations along pre-existing basement faults (e.g., Kazerun Fault, Central Fars, southern Zagros fold-thrust belt, Iran, Sepehr *et al*., 2006; Burberry *et al*., 2011; Motamedi *et al*., 2012). Most notable studies using seismic techniques within cross-strike discontinuity research have been implemented within the Appalachian Thrust Belt, for the identification and analysis of the Anniston, Bessemer and Harpersville transverse zones (e.g., Thomas, 1985; Thomas & Bayona, 2002; Bayona *et al*., 2003; Brewer, 2004). Dataset analyses produced along-strike at specific seismic control points within this region of the southern Appalachians allowed the construction of P-wave velocity models to identify and analyse along-strike, fault-bounded, pre-thrust basement blocks, along-strike changes in depth to basement and their effects on subsequent map-trace deformation of cover strata (Figure 3.4).

Seismic data analyses are important for regional-scale identifications of along-strike changes in subsurface geometries and depth to basement interpretations within regions of poor surface exposure and to focus field research over regional scales. As such, these techniques have been implemented within many cross-strike discontinuity studies (e.g., Thomas, 1985; Thomas & Bayona, 2002; Bayona *et al*., 2003; Brewer, 2004; Brown *et al*., 2007; Cook, 2010). However, large differences in vertical resolution are observed depending on technique applied (e.g., detailed active seismic reflection / refraction profiles within the southern Urals, versus lower resolution passive RF pseudo-migrated survey sections within the Cantabrian Thrust Belt) and large operational costs of such surveys require an economic validation for the use of such methods. Therefore, seismic analyses are normally only implemented within fold-thrust belts with economic viabilities. Combining active and passive surveys improves the constraint on geodynamic evolution within cross-strike discontinuity studies. Advantages and disadvantages of seismic techniques are identified within Table 3.2.

Seismic data analysis		
	Advantages	**Disadvantages**
Reflection (active) surveys	• Mapping of many horizons or layers with each shot • Can delineate very deep density contrasts with much less shot energy and shorter line lengths than comparable reflection techniques • Lateral resolution vastly superior to seismic refraction techniques	• Not unique results – must take care when interpreting the result of a reflection seismic survey • More noise present later in record making reflections difficult to extract from unprocessed data • Lateral resolution degrades with increasing array length and can only be used to depths greater than 15 m due to ground roll and air blast noise • Data acquisition needs much greater amounts of processing than other methods • Higher cost than reflection techniques
Refraction (active) surveys	• Detailed analyses possible over small areas and at depths not exceeding 30 m. Over crustal scales a lower resolution image is produced.	• Only applicable where seismic velocity increase with depth – higher velocity layers overlying lower velocity layers may yield incorrect results • Refraction geophones require arrays 4 to 5 times depth to density contrast. Commonly limited (as a matter of practicality) to depths of less than 30 m – resolution is also decreased
Teleseismic (passive) surveys	• Lower cost than active surveys (reflection / refraction)	• Significantly lower resolutions than those within active surveys (reflection / refraction)

Table 3.2: The advantages and disadvantages of seismic data analysis techniques within cross-strike discontinuity studies

3.1.1.3. Structural contour mapping

Structural contour maps illustrate geometrical configurations of subterranean structural surfaces (e.g., top or bottom of stratigraphical units, marker beds and horizons, unconformities etc.) with respect to a datum, usually sea-level (Groshong, 2006). Subsurface structure maps are generally constructed for specific stratigraphical horizons to indicate, in plan-view, the three dimensional geometrical shapes of horizons (Figure 3.5). Structural contour maps are constructed with the aid of correlation data from well-

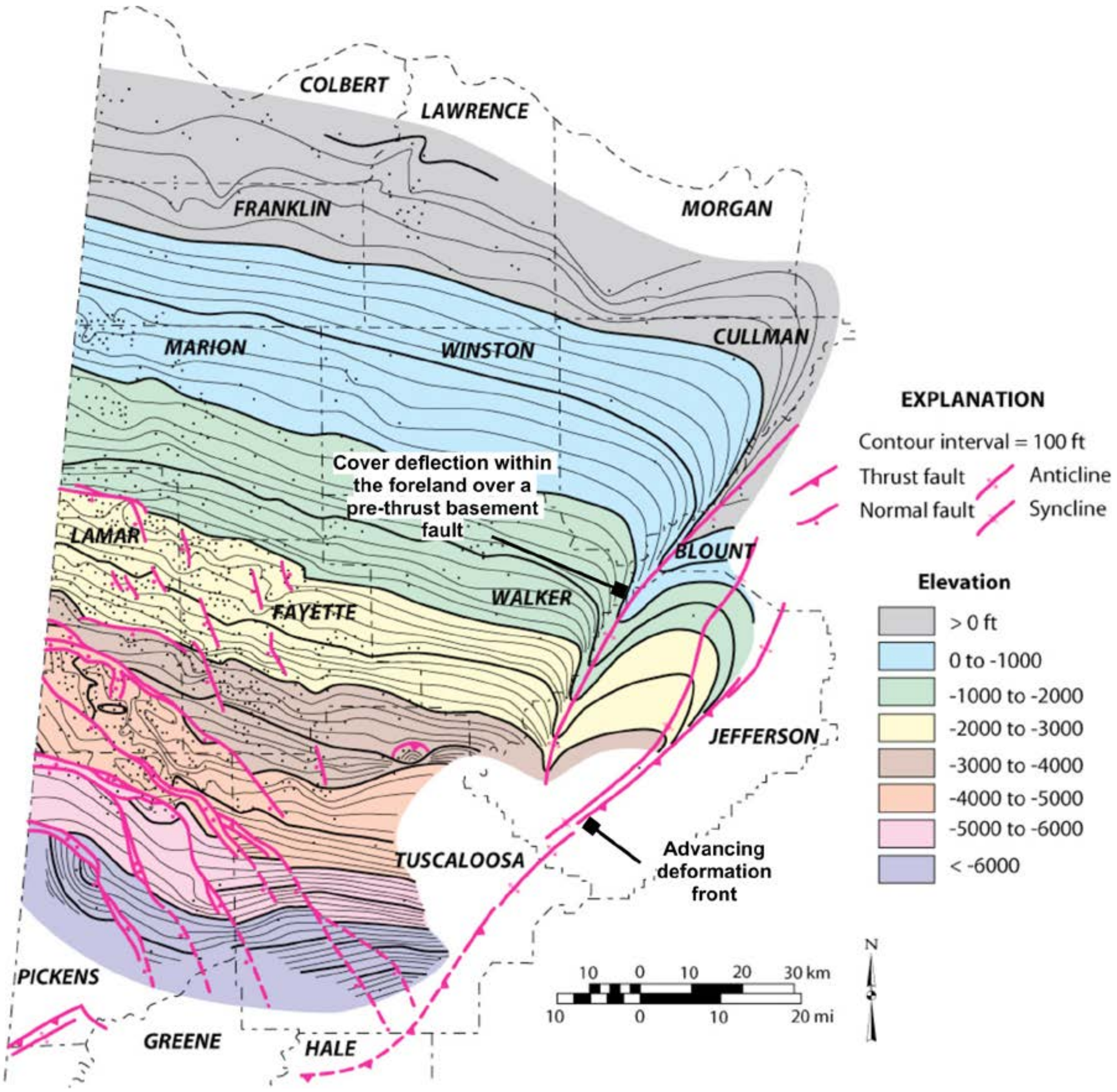


Figure 3.5: Structural contour map of the top of the Tuscumbia Limestone within the Black Warrior Basin of Alabama, southern Appalachian Thrust Belt, depicting along-strike deformation as a result of basement interactions within the foreland of the developing deformation front (adapted after Pashin *et al.*, 2010). Similar diagrams have been used to identify along-strike stratigraphical changes as a result of sub-decollement basement fault interactions and along-strike warps in basement.

logs and seismic section interpretations (Groshong, 2006). On the basis of these data, depth of the structural surface is established at various points in the area under study. Form and depth of occurrence are portrayed by means of structure contour lines, which are constructed in much the same way as contour lines on a topographical map (Figure 3.5; Groshong, 2006). Therefore, an accurate and correct correlation is prerequisite to developing a reasonable along-strike structural interpretation within cross-strike discontinuity research.

Good examples of the use of this technique can be found within Brewer (2004), Pashin *et al*., (2010) and Cook (2010). Within these examples, structural contour maps were used to constrain relationships between the development of the Birmingham Graben system and stratigraphical development within the Bessemer Transverse Zone and adjacent Black Warrior Basin foreland, southern Appalachians, Alabama, USA (Figure 3.5). Deflection of strata within the foreland of the main forelandward propagating deformation front over pre-existing normal and strike-slip / transverse faults were used to identify pre-thrust template normal faults, and to constrain deformation development within the Bessemer Transverse Zone. This is achieved by identifications of along-strike stratigraphical thickness changes, and thereby, identifies along-strike pre-, syn- and / or post-depositional fault movements (e.g., Brewer, 2004; Cook, 2010). Advantages and disadvantages of this technique are summarised within Table 3.3.

Structural contour mapping	
Advantages	**Disadvantages**
• Allow identifications of along-strike changes in lithological thickness as a result of pre-, syn-, and / or post-depositional basement faults • Allow correlation of seismic, well-log and stratigraphical data within a regional context • Allows constraints on the creation of geological surfaces within three-dimensional models • Allows along-strike predictions of lithological outcrop exposure when compared with topographic maps	• Needs a good digital elevation model (DTM) or well-log / seismic to constrain surface and subsurface data with geological model production

Table 3.3: The advantages and disadvantages of structural contour mapping within cross-strike discontinuity studies

3.1.1.4. Well-log data analyses / stratigraphical correlation panel construction

Well logging, also known as borehole logging, is the practice of making a detailed record (i.e., a well log) of geological formations penetrated by a borehole. The log may be based either on visual inspection of samples brought to the surface (i.e., geological logs) or on physical measurements made by instruments lowered into the borehole (i.e., geophysical / wireline logs; Asguith & Krygowski, 2004). Within the oil industry, wireline logs are used to obtain continuous records of a formations rock properties. Wireline logging is performed by lowering a logging tool on the end of a wireline into a borehole or oil well and recording petrophysical properties using a variety of sensors (Asguith & Krygowski, 2004).

Within the Bessemer Transverse Zone and the foreland Black Warrior Basin, well-log data sets, particularly gamma ray log data sets, have been used from oil wells to identify along-strike changes of stratigraphical thickness and potential basement fault continuations into foreland settings (e.g., Brewer, 2004; Pashin *et al*., 2010). Gamma ray logging is a wireline logging method used to measure naturally occurring gamma radiation to characterise rock or sediment in a borehole. Different rock types emit different amounts and different spectra of natural gamma radiation. In particular, mudstones usually emit more gamma rays than other sedimentary rocks, such as sandstone, coal, dolostone or limestone (Asguith & Krygowski, 2004). This difference in lithological radioactivity allows the gamma tool to distinguish along-strike changes in stratigraphy and stratigraphical thicknesses (Asguith & Krygowski, 2004; Figure 3.6).

Analysis of well-log data sets allows the creation and constraint of stratigraphical correlation panels and isopach diagrams. Stratigraphical correlation panels are constructed to establish the geochronological relationships between different areas, based on geological investigations of many local successions either within the subsurface within well data or during field data collection (Tearpock & Bischke, 2002; Stanley, 2005). Therefore, along-strike variations identified in individual well-log data sets can be correlated over regional scales (e.g., Tull, 2002; Bayona & Thomas, 2006; Pashin *et al*., 2010; Figure 3.6).

Along-strike across the Bessemer Transverse Zone and adjacent foreland Black Warrior Basin, well-log data sets and stratigraphical correlation panels have been used to identify distinct along-strike thickness changes indicative of lithological responses to syn-depositional reactivations of basement faults during the Alleghanian Orogeny, especially within Mississippian stratigraphy such as the Chattanooga Shale (Cook, 2010; Figure 3.6). Results within these cross-strike discontinuity studies provide greater insight into the development of the pre-thrust template pre-, syn- and post-allochthon formation. However,

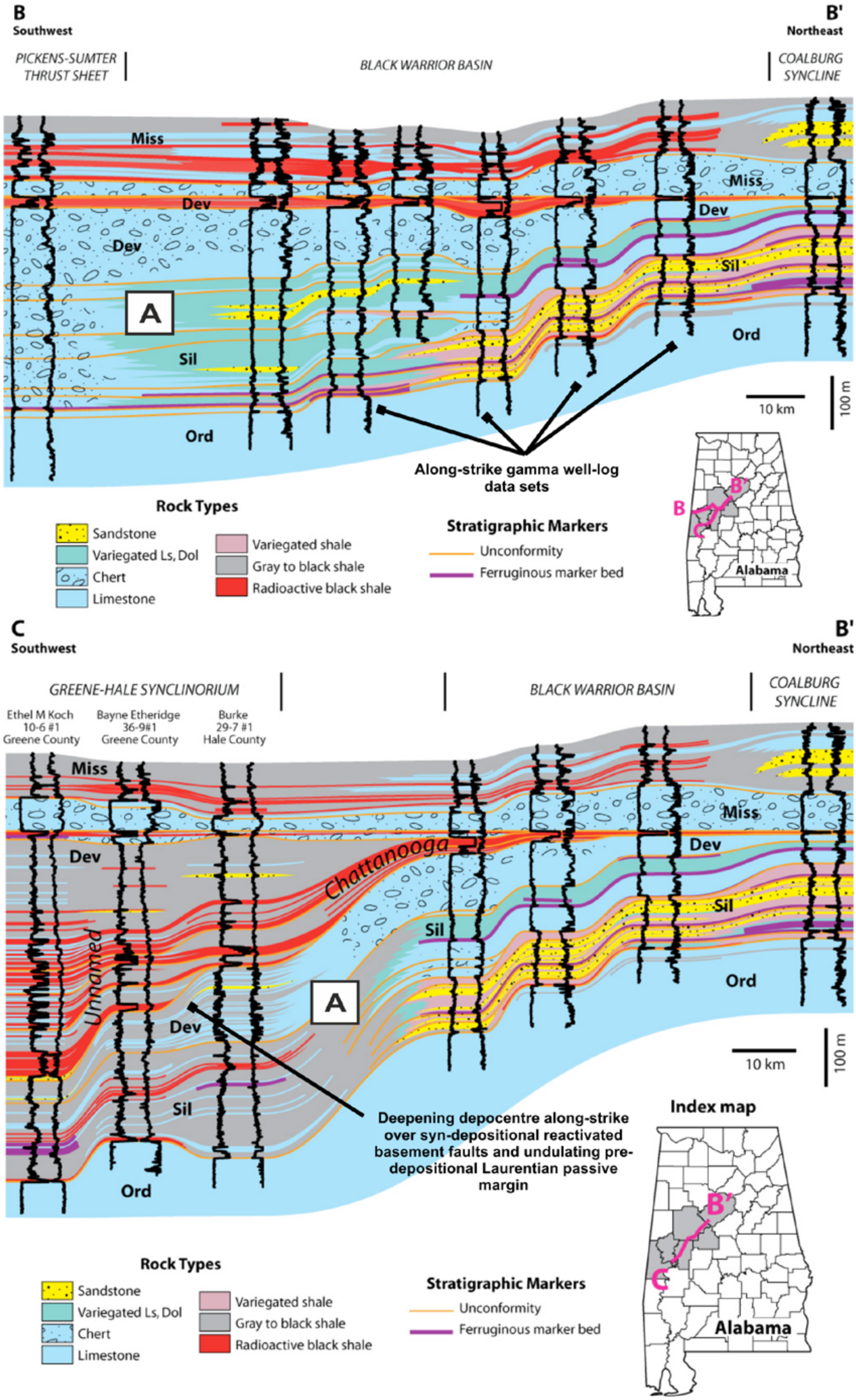


Figure 3.6: Stratigraphical correlation panels within the Black Warrior Basin, southern Appalachians, Alabama, constrained by gamma ray logs derived from well-log data sets. Along-strike thickness changes within the foreland of the Bessemer Transverse Zone indicate syn-depositional basement fault reactivations during the Alleghanian Orogeny, especially on Mississippian strata, such as the Chattanooga Shale **(A)** (Pashin *et al.*, 2010).

use of well-log data sets is still mainly only accessible within foreland regions, such as the Black Warrior Basin, where an economic validation for its implementation is required (e.g., hydrocarbon exploration; Goffey *et al*., 2010). Advantages and disadvantages of well-log data analyses and stratigraphical correlation panels are identified in Table 3.4.

Well-log data analyses, stratigraphical correlations and Isopach maps		
	Advantages	**Disadvantages**
Well-log data analyses	• Identification of along-strike variations in stratigraphical thickness • Allow identifications of along-strike changes in stratigraphy in areas of poor exposure and deep stratigraphical analyses • Individual technique such as gamma-ray logging allow along-strike correlations of petrophysical properties • Allow construction of isopach diagrams and correlation panels along-strike	• Cost – only undertaken in regionals of economic viability • Technique generally only applied within foreland areas (i.e., areas of potential hydrocarbon interest) • Restricted use of data sets – new data sets may not be able to be published or accessed during exploration phases
Stratigraphical correlation panels / isopach maps	• Allow identifications along-strike of stratigraphical thickness and / or facies changes within a two and three dimensional context • Identification of potential basement faults and / or basement-related warps / irregularities within foreland areas along-strike • Technique can be applied in various structural settings	• In areas of poor exposure, stratigraphical correlation panels and isopach maps require constrains against other techniques such as, well-log data. • As such, quality of correlations and stratigraphical thickness variations are only as good as the number of well-log observations.

Table 3.4: The advantages and disadvantages of well-log data analyses and stratigraphical correlation panels within cross-strike discontinuity studies

3.1.1.5. Isopach analyses

Isopach map analyses illustrate along-strike thickness variations within a tabular unit, layer or stratum in a direction that is perpendicular to the layer boundaries; hence isopachs are contour lines of equal thickness over an area (Levorsen, 1967; Tearpock & Bischke, 2002). Within cross-strike discontinuity studies, isopach map analyses have been implemented to identify along-strike changes in stratigraphical thickness, especially along the lower-most stratigraphical horizons, as these display impacts of pre-thrust template irregularities most clearly (i.e., irregular basement as a result of erosion prior to stratigraphical deposition and / or effects of pre-, syn and / or post-depositional basement faults; Brewer, 2004; Pashin *et al.*, 2010; Cook, 2010; Figure 3.7).

Notable utilisations of this technique are identified within foreland portions of the Bessemer Transverse Zone, Black Warrior Basin, where along-strike variations of stratigraphical thickness of the Chattanooga Shale have been used to identify syn-depositional basement-related fault reactivations and their effects on along-strike Mississippian stratigraphical deposition (e.g., Chattanooga Shale; Brewer, 2004; Pashin *et al.*, 2010; Cook, 2010; Figure 3.6; 3.7). Correlations of well-log data analyses, stratigraphical correlation panels and isopach analyses allow regional-scale observations along many individual well sites to be visualised. Furthermore, potential areas of detailed study for cross-strike discontinuity and transverse zone identification are observed. Advantages and disadvantages of this technique are summarised within Table 3.4.

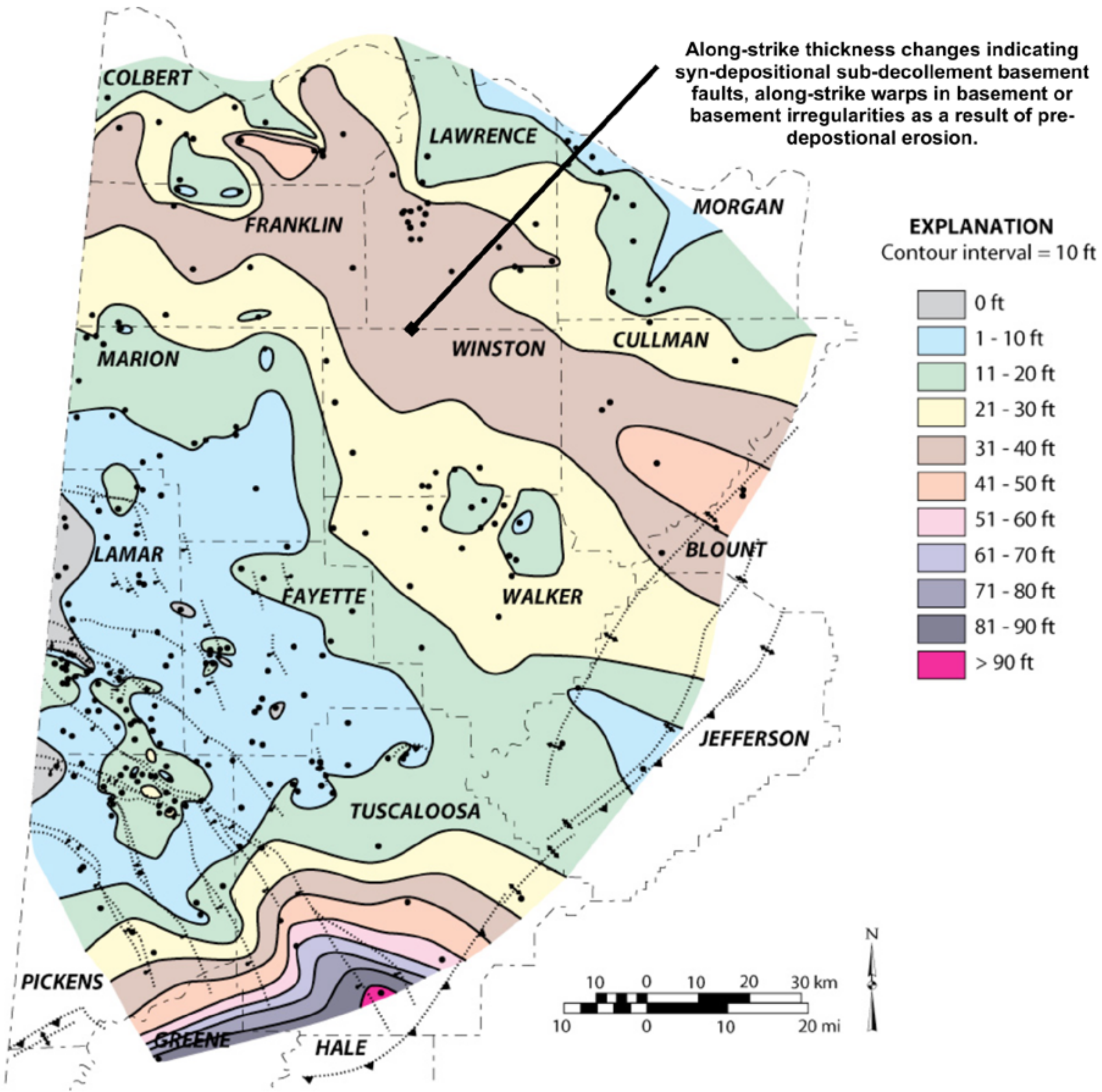


Figure 3.7: Isopach map of the Chattanooga Shale within the foreland of the Bessemer Transverse Zone in the adjacent Black Warrior Basin of Alabama, southern Appalachian Thrust Belt (Pashin *et al.*, 2010). Similar isopach maps have been used to identify along-strike stratigraphical thickness changes as a result of syn-depositonal, sub-decollement basement fault interactions, along-strike warps in basement and basement irregularities as a result of pre-depositional erosion.

3.1.1.6. <u>Sedimentary facies / provenance analyses</u>

Sedimentary facies analyses have been implemented within many fold-thrust belt studies (e.g., Thomas, 1985; Woodward, 1987b; Reading 1996; Tull, 2002; Bayona *et al*., 2003; Brewer, 2004; Stanley, 2005; Tull & Holm, 2005; Bayona & Thomas, 2006; DeCelles & Coogan, 2006; Kwon & Mitra, 2006; Cook, 2010; Turner *et al*., 2010; Pashin *et al*., 2010). Sedimentary facies analyses are commonly undertaken through regional observations of stratigraphical successions from field data collections, allowing production of stratigraphical correlation panels and stratigraphical facies fence diagrams to place along-strike variations within a three-dimensional context (e.g., Cain, 2009; Cook, 2010; Pashin *et al*., 2010; Figure 3.6; 3.8). Within south-east Utah, Cain (2009) utilised such techniques to identify along-strike facies changes associated with deposition of the Permian Organ Rock Formation within an extensional setting. Results suggest that along-strike facies changes were controlled by proximal, medial and distal alternations across foreland irregularities, examples of which are similarly found where transverse zones alter point-sources of deposition (e.g., Charleston Transverse Zone, south Provo Salient, Sevier fold-thrust belt, Utah: Aschoff *et al*., 2011).

Stratigraphical provenance analyses (i.e., analyses of sediment production and composition of sediment parent rock; Weltje & von Eynatten, 2004; Weltje, 2012 and references therein) have been implemented to determine along-strike sediment transport pathways within fold-thrust belts (e.g., Bayona, 2003; Aschoff *et al*., 2011; Díez Fernández *et al*., 2012). Stratigraphical provenance analyses are undertaken through detailed geochemical studies of sediments including, microscopic-morphological techniques, geochemical techniques and radiometric dating of detrital mineralogies. Greater details of geochemical techniques utilised for provenance analysis can be identified within Weltje & von Eynatten (2004) and Weltje (2012).

Within cross-strike research, sedimentary facies and provenance analyses have been used in both modern and ancient analogues to determine pre-, syn- and / or post-depositional fault activity and its implications for pre-thrust sediment distribution pathways, compartmentalisation and stratigraphical deposition (e.g., Thomas, 1985; Cook, 2010; Aschoff *et al*., 2011). Aschoff *et al*., (2011) working within modern day Asian and South American transverse zones, identified that sediment compartmentalisation occurred

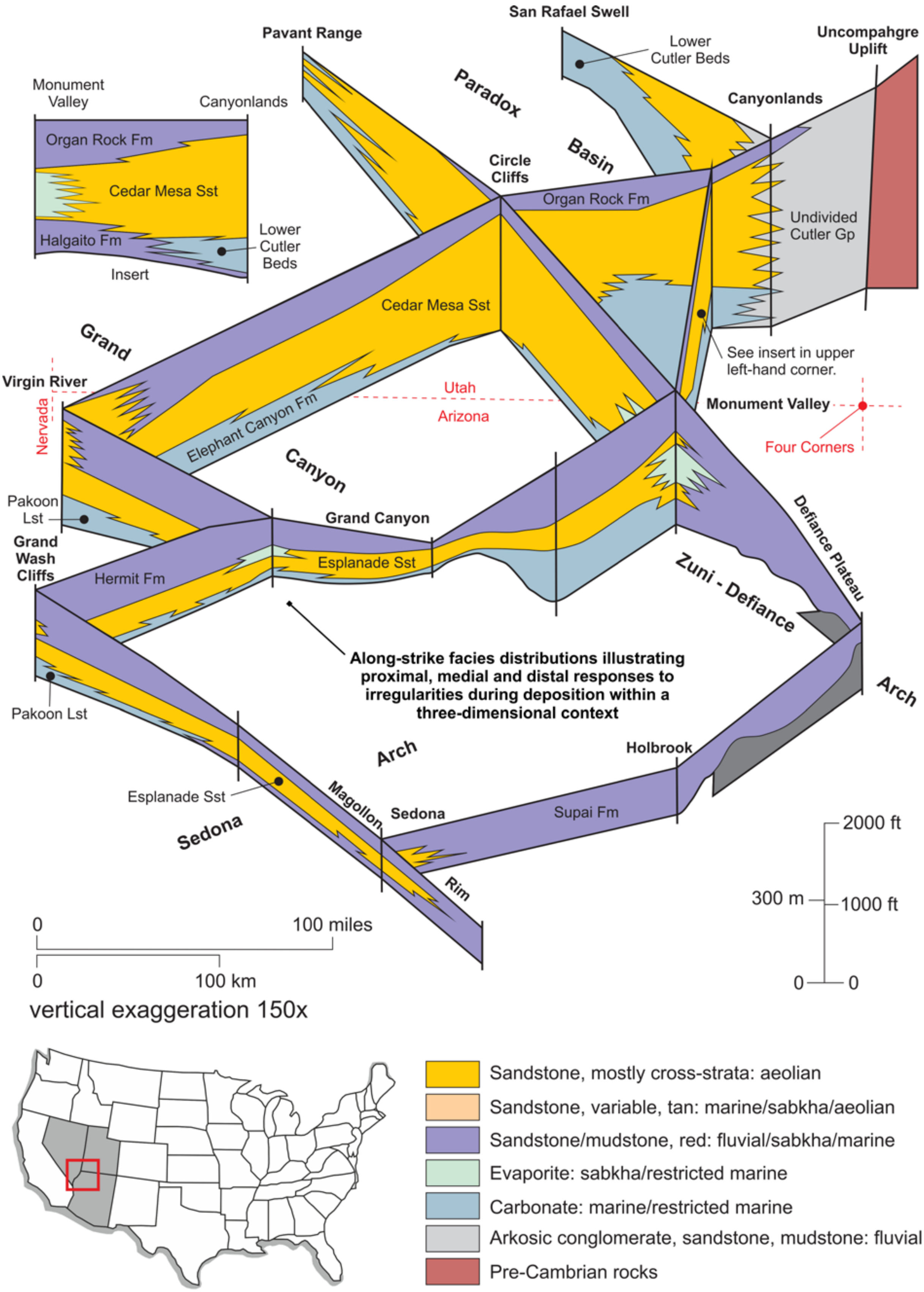


Figure 3.8: Fence diagram showing the regional distribution of major stratigraphical/facies units within southern Utah and northern Arizona (Adapted after Cain, 2009). Such regional-scale analyses of facies distribution allow along-strike discontinuities to be identified during detailed field analyses and placed within a three-dimensional context.

during transverse zone development and compared this to results within an ancient analogue (i.e., Charleston Transverse Zone, south Provo Salient), which identified similar regional-scale results. Further analyses are observed within the Appalachian fold-thrust belt in Alabama and Georgia, along the Bessemer, Harpersville, Anniston and Rising Fawn transverse zones (e.g., Brewer, 2004; Tull & Holm, 2005; Bayona & Thomas, 2006; Cook, 2010). Advantages and disadvantages of sedimentary facies / provenance analyses are identified within Table 3.5.

Sedimentary facies and provenance analyses	
Advantages	**Disadvantages**
• Allow regional-scale correlations of stratigraphical sequences. Useful for exploration strategies. • Identify potential compartmentalisations along-strike of sediments in response to basement-related faults and / or fault activity. • Useful for load analyses along-strike to determine flexural subsidence and accommodation patterns and allow determinations of sediment point sources (e.g., Aschoff *et al*., 2011)	• Detailed geochemical techniques developed within provenance studies costly to implement. • Need sediments which are able to be analysed and have not been geochemically altered by later tectonic overprinting.

Table 3.5: The advantages and disadvantages of sedimentary facies and provenance analyses within cross-strike discontinuity studies

3.1.1.7. Stratigraphical separation diagrams

Stratigraphical separation diagrams (SSDs) have been extensively used for lateral ramp identifications within stratigraphical sections in many fold-thrust belt settings. Since Froidevaux (1968) and Bielenstein (1969) pioneered the use of stratigraphical separation diagrams, numerous examples have been used globally within cross-strike discontinuity research, ranging from the Sevier fold-and-thrust belt, central Utah, (e.g., DeCelles & Coogan, 2006; Kwon & Mitra, 2006) to the Keping Shan Thrust Belt, southwest Tien Shan foreland, China (e.g., Turner *et al*., 2010). This methodology has been described as a 'cheap but neglected' tool of analysis, which allows interpretations of both fault-surface geometry and mechanism of faulting (Knížek *et al*., 2009).

Analysis of faults in sediments is based on the study of geometrical components of displacement and fault surface geometry in relation to bedding (Knížek *et al*., 2010). Fault cut-off geometries at deeper levels can be represented in three-dimensional models or in two-dimensional Allan diagrams (Allan, 1989). However, SSDs can be quantatively constructed using surface trace data from geological maps, whereas three-dimensional Allan diagrams require data for spatial positions of fault and stratigraphical-marker surfaces at depth (i.e., exact location of cut-off lines, branch-lines and tip-lines; Knížek *et al*., 2010).

Two principal types of SSD, based on the relation of fault traces in map-view to the direction of tectonic transport, have been used in previous analyses:

1. <u>Transport-parallel SSDs</u>: Stratigraphical separation taken from transverse cross-sections, where the fault trace is parallel to tectonic transport (Knížek *et al*., 2010, and references therein)

2. <u>Transport-perpendicular SSDs</u>: Stratigraphical separation taken from longitudinal cross-sections. In the case of thrusts, fault trace is perpendicular to tectonic transport, but parallel to the fault strike line (e.g., Woodward, 1987b; Brewer, 2004; Kwon & Mitra, 2006; Knížek *et al*., 2010). Longitudinal SSDs (transport-perpendicular) are the most useful within transverse zone research.

Stratigraphical separation diagrams are based on the relationship between the separations of two parts of one horizon displaced along a fault surface. Displacements can be described in terms of two key parameters: slip and separation (Reid *et al*., 1913). Slip is the relative movement along the fault surface. In contrast to slip, 'separation' is designated as the real distance between two parts of one surface disrupted by the fault (Knížek *et al*., 2009). It is possible to measure several types of separation depending on observed direction (i.e., 'vertical separation' measured in the vertical direction, 'offset' in the horizontal plane at right angles to strike of the bed, 'strike separation' in the fault direction, 'stratigraphical separation' laterally along the fault trace, and 'dip separation' in the fault dip direction (Figure 3.9). A full review of stratigraphical separation diagram development and utilisation can be found in Knížek *et al*., (2009, 2010) and Knížek & Melichar, (2011).

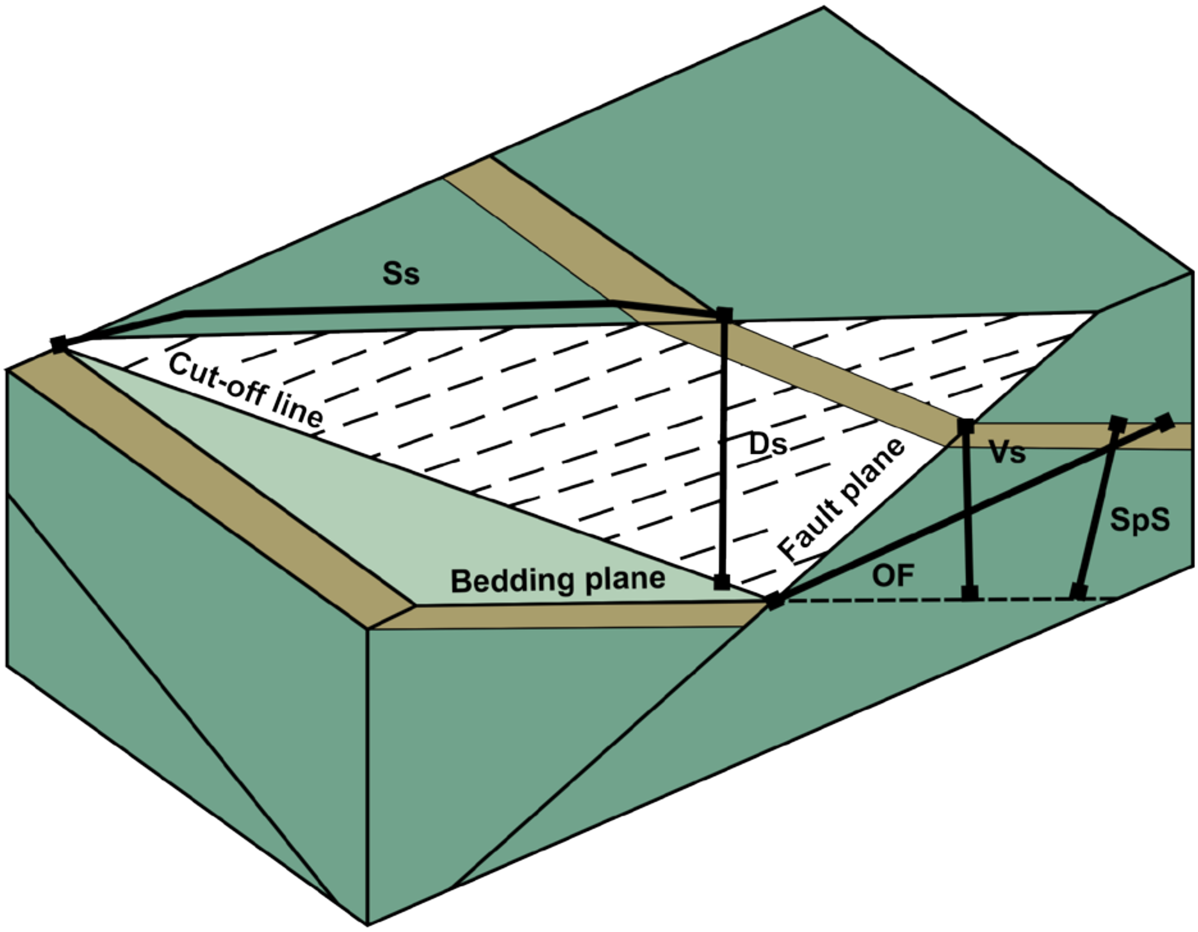


Figure 3.9: Definition of fault slips and separations using a bedding plane disrupted by fault: separation components separations: Ss - strike separation, Ds - dip separation, Vs - vertical separation, OF - offset, SpS - stratigraphic separation. (Adapted after Knížek *et al*., 2010).

Commonly, transverse zone studies have focussed on ‘stratigraphical separation’, (i.e., thickness of strata that originally separated two beds brought into contact at a fault along the lateral trace of individual thrust fault map traces, Knížek *et al*., 2009). Methodology allows stratigraphical separation between footwall and hanging-wall to be determined over various scales laterally along thrust fault traces. In this way, the two lines in the diagram representing the footwall and hanging-wall represent stratigraphical levels of two fault walls (Figure 3.10).

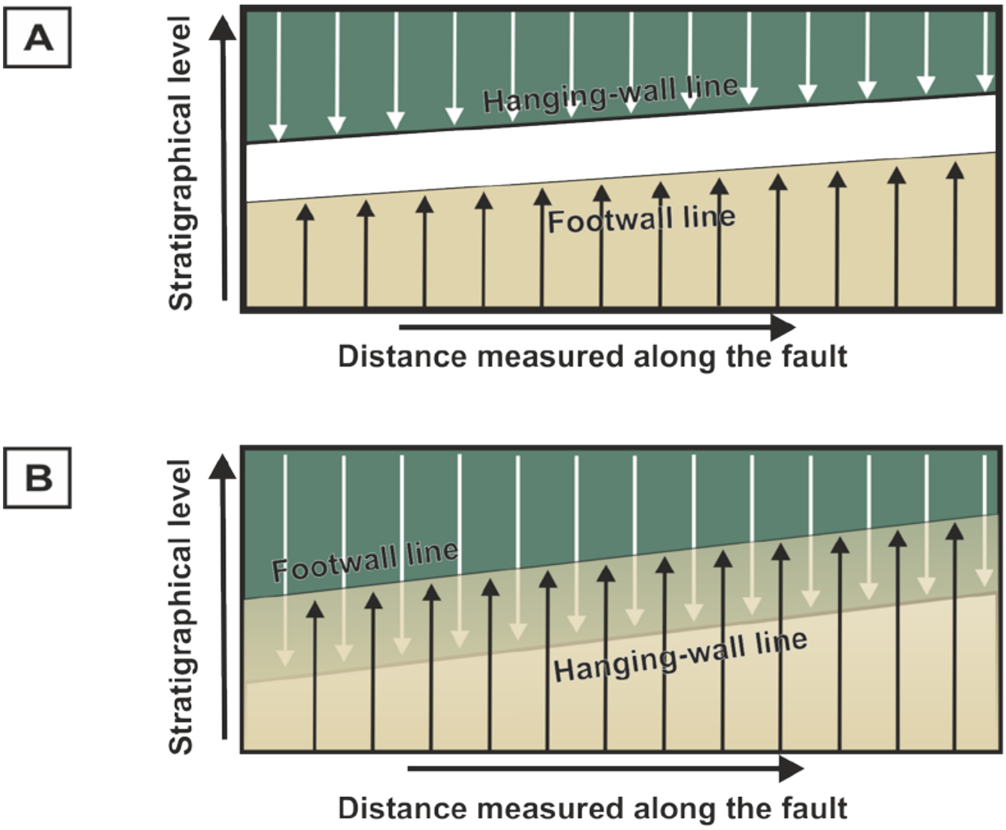


Figure 3.10: Diagrams depicting stratigraphical gaps **(A)** (hanging-wall above footwall within the map-view thrust trace sequence) and stratigraphical duplications **(B)** (footwall structurally above the hanging-wall within the map-view thrust trace sequence).(Adapted after Knížek *et al*., 2010).

Relative positions of hanging-wall and footwall lines on stratigraphical separation diagrams indicate two possible occurrences along a fault trace (Figure 3.10):

- Line representing the stratigraphical level of the hanging-wall is situated above the footwall line, denoting a clear stratigraphical gap in the SSD; characteristic of extensional faults (Figure 3.10a).
- The footwall line is above the hanging-wall, indicating a stratigraphical duplication along the fault; characteristic of thrust faults (Knížek *et al*., 2009; Figure 3.10b)

Within stratigraphical separation analyses, various geometrical possibilities can be produced along a fault trace (Appendix C). Sudden changes in stratigraphical levels within the SSD in both the footwall and hanging-wall indicate cross-cutting by younger transverse faults. Transverse faults commonly compartmentalise differential displacements within thrust systems, creating lateral variations along strike (Thomas, 1990). In thrusts, steps (ramps) typically appear in distinct position on both fault wall lines; while long horizontal footwall and hanging-wall plots mark structural flats (décollements) creating ramp-flat-ramp geometries (Figure 3.11a). Greater detailed discussions of various ramp type geometries can be found within Wilkerson *et al*., (2002).

Identifications of ramp-flat geometries and compartmentalisation along transverse faults are essential to identify regions where transverse structures and / or cover deformation over such structures may be observed within the pre-thrust template (e.g., Ramsay, 1992; Butler *et al*., 2010; Figure 3.11b). Such observations may depict cross-strike discontinuities within potential transverse zones settings, such as the Lemington Zone, Sevier Thrust Belt, Utah (e.g., Kwon & Mitra, 2006). Stratigraphical separation diagrams are important for understanding lateral lithofacies and thickness variations within the deforming sedimentary wedge (e.g., Wilkerson *et al*., 2002) and their relation to potential changes in regional thrust décollements / detachments along major faults. Therefore, analysis of stratigraphical separation can only be used in areas with well-documented and constrained (tectono-) stratigraphical sequences, such as the Appalachians, Apennines, and the Moine and Cantabrian thrust belts. As such, utilisation of this technique is varied within cross-strike discontinuity / transverse zone research, but prevalent within global analysis of thrust belts. Advantages and disadvantages are summarised within Table 3.6.

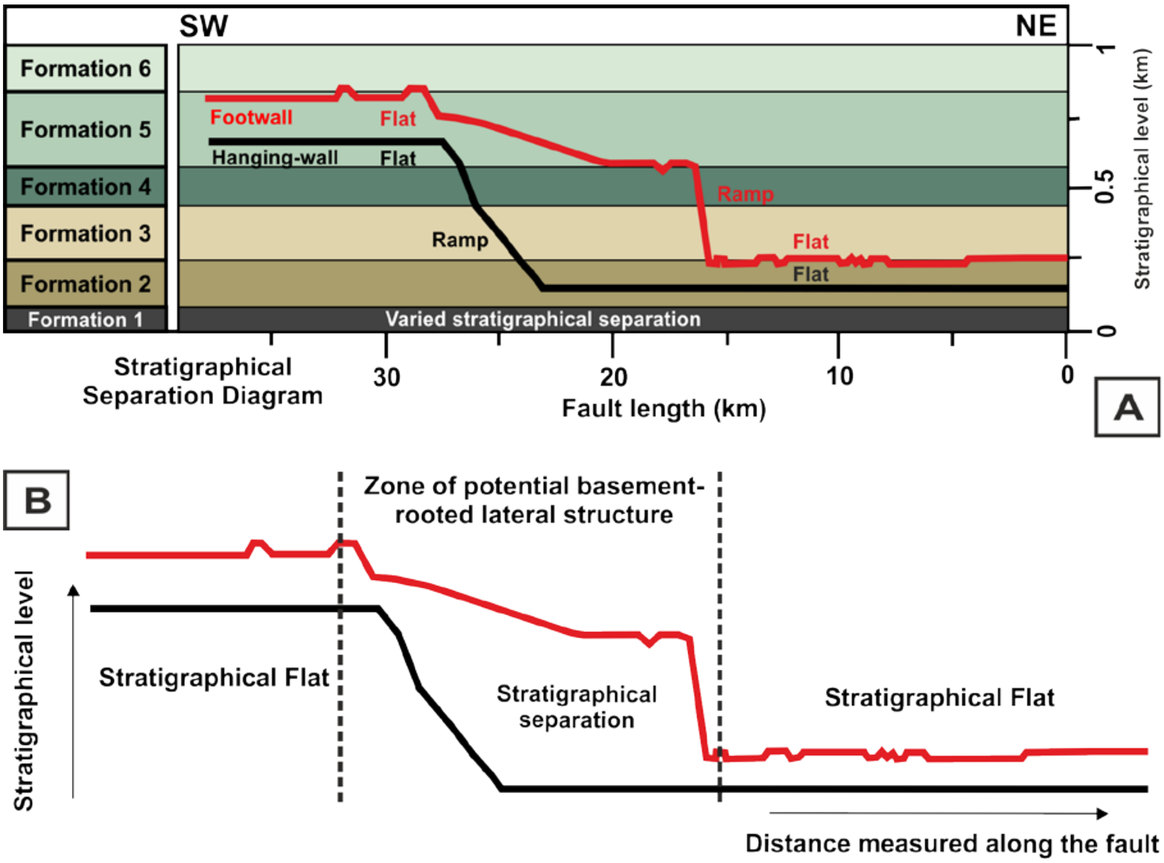


Figure 3.11: **(A)** Transport-perpendicular stratigraphical separation diagram depicting along-strike footwall and hanging-wall relationships within a flat-ramp-flat sequence (Adapted from Knížek *et al.*, 2010). **(B)** Geometrical relationships highlighted within the stratigraphical separation diagram allow regional analyses of thrust decollement and lithological relationships to be determined. In this way, zones where potential basement-rooted structures within the pre-thrust template are viewed may be analysed in greater detail within the study areas.

Stratigraphical separation diagrams	
Advantages	**Disadvantages**
• Identify along-strike separations between hanging-wall and footwall units indicating potential lateral structures • Identification of lateral lithofacies / thickness variations within the deforming sedimentary wedge and their relation to potential changes in regional thrust décollements / detachments along major faults • Technique which can be applied over various scales either during field investigations or prior to field investigations to focus areas of study	• Can only be used in areas with well-documented and constrained (tectono-) stratigraphical sequences

Table 3.6: The advantages and disadvantages of stratigraphical separation diagram analyses within cross-strike discontinuity studies

3.1.2. Detailed regional- and local-scale field studies

Integrated studies of geological map analyses and / or geological mapping incorporating geometrical and kinematic data collections, cross-section constructions and palinspastic restorations are common within transverse zone studies (e.g., Thomas, 1990; Thomas & Bayona, 2002; Brewer, 2004; Cook, 2010; Krabbendam & Leslie, 2010; Leslie *et al*., 2010). The following subdivisions within this section review the use of each of these components in greater detail.

3.1.2.1. <u>Geological map analyses and geological mapping</u>

Cross-strike discontinuity linkages and phenomena within transverse zones commonly have abrupt (rather than gradual) terminations along-strike, which can be identified over a range of map-scales, types and offsets (Thomas, 1990). Wheeler (1980) and Thomas (1990) identified that localised cross-strike discontinuities and, on larger scales, transverse zones which transect the entire thrust belt, require detailed analyses of geological maps and / or new field data collection during geological mapping. As such, analyses of geological maps and / or detailed field data collection during geological mapping studies comprise a prerequisite for analysis of along-strike variations in geometrical structures in map-view (Wheeler, 1980; Thomas, 1990; Berger, 2001). Advantages and disadvantages of geological map analyses and geological mapping are identified within Table 3.7.

Geological map analyses, geological mapping and geometrical / kinematic data collection		
	Advantages	**Disadvantages**
Geological map analyses	• Identification of along-strike variations in structural styles over a variety of scales • Desk-based technique which can be implemented prior and during field data collections	• Previous geological map observations require validation. Maps only as good as the original interpretation and scale of detail during field analysis (regional v. local scales) • Not always economically / politically viable depending on location of study area
Geological mapping	• Development of digital mapping techniques allow re-interpretations during field data collection • Collection of new geometrical and kinematic datasets and / or validations of previous interpretations	• Not always possible – dependent on outcrop exposure and socio-political constraints • Quality of observations only as good as the geologist taking the primary data
Geometrical and kinematical data collection	• Identification of along-strike variations in structural styles • Identification of thrust kinematics (foreland- versus hinterland-propagating thrust systems) • Identification of along-strike variations in regional transport and / or localised vertical-axial rotations of thrust sheets	• Not always possible – dependent on outcrop exposure and socio-political constraints • Quality of observations only as good as the geologist taking the primary data

Table 3.7: The advantages and disadvantages of geological map analyses, geological mapping techniques and geometrical / kinematic data collections within cross-strike discontinuity studies.

3.1.2.2. Geometrical and kinematic data collection / analyses

A plethora of detailed field studies have been undertaken to identify geometrical and kinematic evolutions for cross-strike discontinuities within various fold-thrust belts globally (e.g., Schönborn, 1990; Bulnes & Marcos, 2001; Price, 2001; Bayona *et al*.,2003; Holdsworth *et al*., 2007; Mookerjee & Mitra, 2009; Bonini *et al*., 2010; Pace *et al*., 2012a, 2012b). Structures transverse (or oblique) to the thrust belt provide links across strike between the ends of strike-parallel fault ramps (Thomas, 1990). However, a lack of subsurface data often makes it difficult to determine geometrical and kinematic linkages between different tectonic units along-strike. Cross-strike linkages are commonly identified in map-view as along-strike terminations of thrust faults and ramp anticlines; by curves and offsets in strike; by along-strike changes in angle and direction of fold plunge, direction of fold and thrust vergence, stratigraphical level of detachment and structural style (e.g., Thomas, 1990; Paulsen & Marshak, 1997, 1998; Brewer, 2004; Tull & Holm, 2005; Kwon & Mitra, 2006, 2012; Yassaghi & Madanipour, 2008; Cook & Thomas, 2009; Cook, 2010).

Within cross-strike discontinuity and transverse zone research, geometrical and kinematic analyses seek to determine the evolution of cross-strike discontinuity phenomena and identify cross-strike linkages. This has commonly been achieved through collection of structural and kinematic data (e.g., slickenlines and kinematic indicators); photographic data of thrust fault and fold geometries (e.g., hanging-wall anticlines; Calamita *et al*., 2011), and branch-line, fault-tip line and fault cut-off point analyses for lateral ramp identifications (e.g., Elliott & Johnson, 1980; Coward, 1985; Ramsay, 1992; Butler, 2004; Krabbendam & Leslie, 2004; Kwon & Mitra, 2006; Butler, 2010).

Analyses of geometrical and kinematic styles are crucial for determining thrust sequences, for identifying cross-cutting relationships, and to determine potential along-strike differential rotations, either as a result of rotational thrusting or post-thrusting vertical-axial rotations of thrust sheets (Allerton *et al*., 1993; Allerton, 1998). Furthermore, analyses of along-strike variations in geometrical and kinematic style allow determinations of whether present structures were generated by a single deformation episode or by multiple phases of deformation. If deformation did, in fact, occur in two phases, then interference structures (i.e., fold overprint or accommodation structures, such as superposed thrust faults) should be apparent. Contrarily, if there were one single transport direction or deformation phase, than an altogether different, yet no less complex, set of structures must result (e.g., Cook, 2010).

Along-strike analyses of branch-line, fault-tip line and fault cut-off analyses within fold-thrust belt studies have commonly focused on amounts of displacement along individual thrust faults and thrust sheets (e.g., Elliott & Johnson, 1980; Coward, 1985; Butler *et al*., 2004). However, these analyses also allow identification of lateral thrust fault terminations and thrust propagation sequences (e.g., Krabbendam & Leslie, 2004). Two (end-member) geometries are possible, each suggesting a different sequence of thrusting (Figure 3.12). In Figure 3.12a, lower thrust A is cut off by upper thrust B. This would occur if thrust activity steps back and upwards, so that thrust B is younger than thrust A (i.e., an out-of-sequence or hinterland-propagating thrust sequence). Within this thrust sequence, the lower thrust A is expected to be planar (unless folded by later events) and that thrust B progressively cuts off the stratigraphy of thrust sheet A along-strike (Krabbendam & Leslie, 2004; Figure 3.12a). Conversely, a different geometry is expected within a foreland-propagating thrust sequence (Figure 3.12b, 3.12c; Elliott & Johnson, 1980; Krabbendam & Leslie, 2004). Within these geometries the lowest thrust would be the most recently active and truncates the inactive section of the upper thrust B (Figure 3.12c).

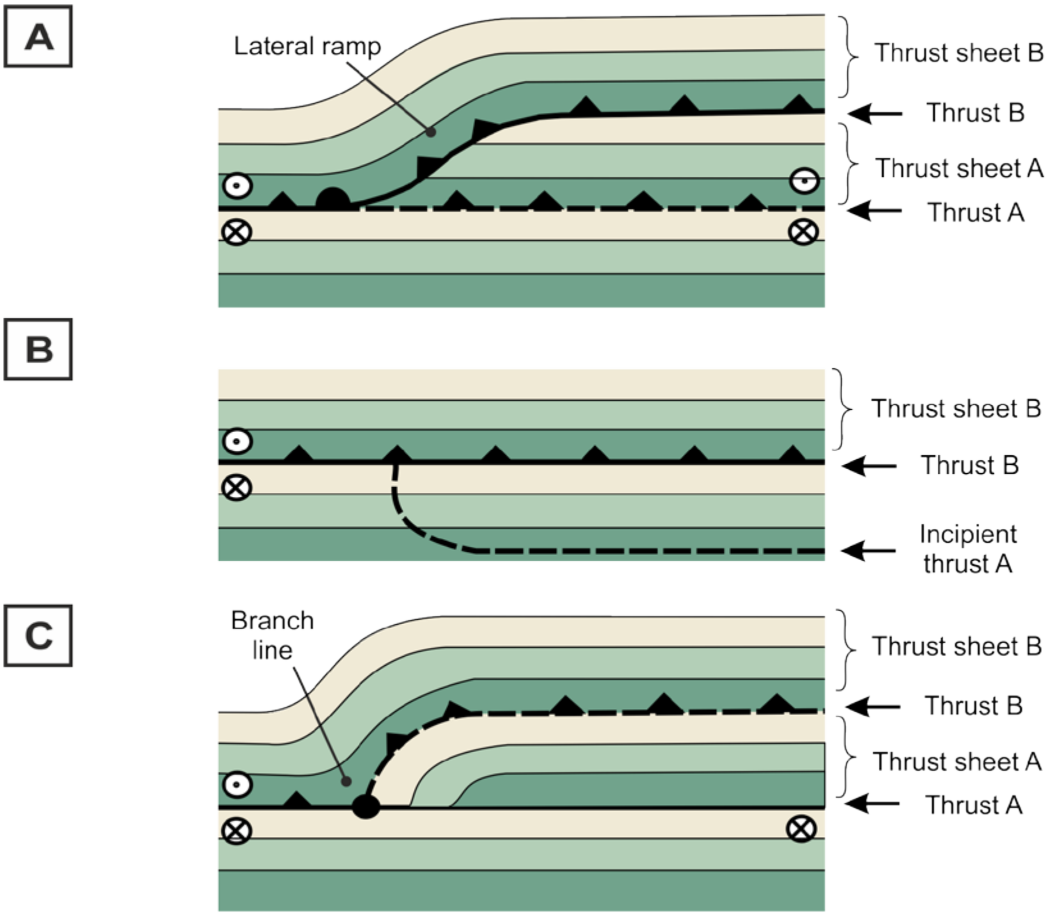


Figure 3.12: Lateral thrust geometries. **(A)** Hinterland-propagating thrust sequence (Out-of-sequence thrust propagation) with thrust B cutting out thrust A along-strike. **(B)** Foreland-propagating thrust sequence. Incipient thrust A is the most recently active resulting in the along-strike cut-off of thrust B which is passively carried creating a monocline within the hanging-wall of thrust A **(C)**. All diagrams have transport direction towards the viewer (Krabbendam & Leslie, 2004)

Detailed analyses of geometrical styles and kinematic indicators, allow the regional transport direction to be determined within the thrust system. Kinematic data is then summarily presented within stereonet analyses. Regional transport identification allows the alignment of transport-parallel and transport-lateral cross-sections. A detailed review of the uses of kinematic indicators can be found within Cosgrove (2007). Advantages and disadvantages of geometrical and kinematic data analyses are summarised in Table 3.7.

3.1.2.3. Cross-section construction

Cross-sections are constructed to determine internal geometries within the subsurface along the intersection of a three-dimensional body with a two-dimensional plane (e.g., Suppe, 1985; Bayona *et al*., 2003). Two varieties of cross-sections are utilised within transverse zones studies, transport-parallel and transport-lateral cross-sections. Transport-parallel (strike-perpendicular) cross-sections have been produced by many previous works to determine thrust architectural geometries parallel to the transport direction (e.g., Butler *et al*., 2007; Krabbendam & Leslie, 2010; Leslie *et al*., 2010; Turner *et al*., 2010). Within the Traligill Transverse Zone, construction of transport-parallel cross-sections allowed the development of structures within the transport direction, such as the Beinn nan Cnaimhseag Klippe and Breabag Dome within the Breabag-Stronchrubie system, to be analysed and interpreted to determine the pre-thrust template role during development (Krabbendam & Leslie, 2010; Figure 3.13a).

Whilst many authors have produced transport-parallel (strike-perpendicular), far fewer have constructed transport-lateral (strike-parallel) cross-sections within transverse zone research (e.g., Brewer, 2004; Kwon & Mitra, 2006; Krabbendam & Leslie, 2010; Leslie *et al*., 2010; Figure 3.13b). Transport-lateral cross-sections are constructed to determine lateral changes in thrust décollements, cross-strike linkages and potential pre-thrust lateral variations within cross-strike discontinuity research (e.g., Thomas & Bayona, 2002; Turner *et al*., 2010). Within the Traligill Transverse Zone, transport-lateral cross-sections were produced to determine the along-strike development of structures such as the Droighinn Anticlinal Stack. This structure developed as a result of localised buttressing and transpression along a one hundred metre step in basement coincident with the Loch Assynt Fault (Krabbendam & Leslie, 2010; Figure 3.13b).

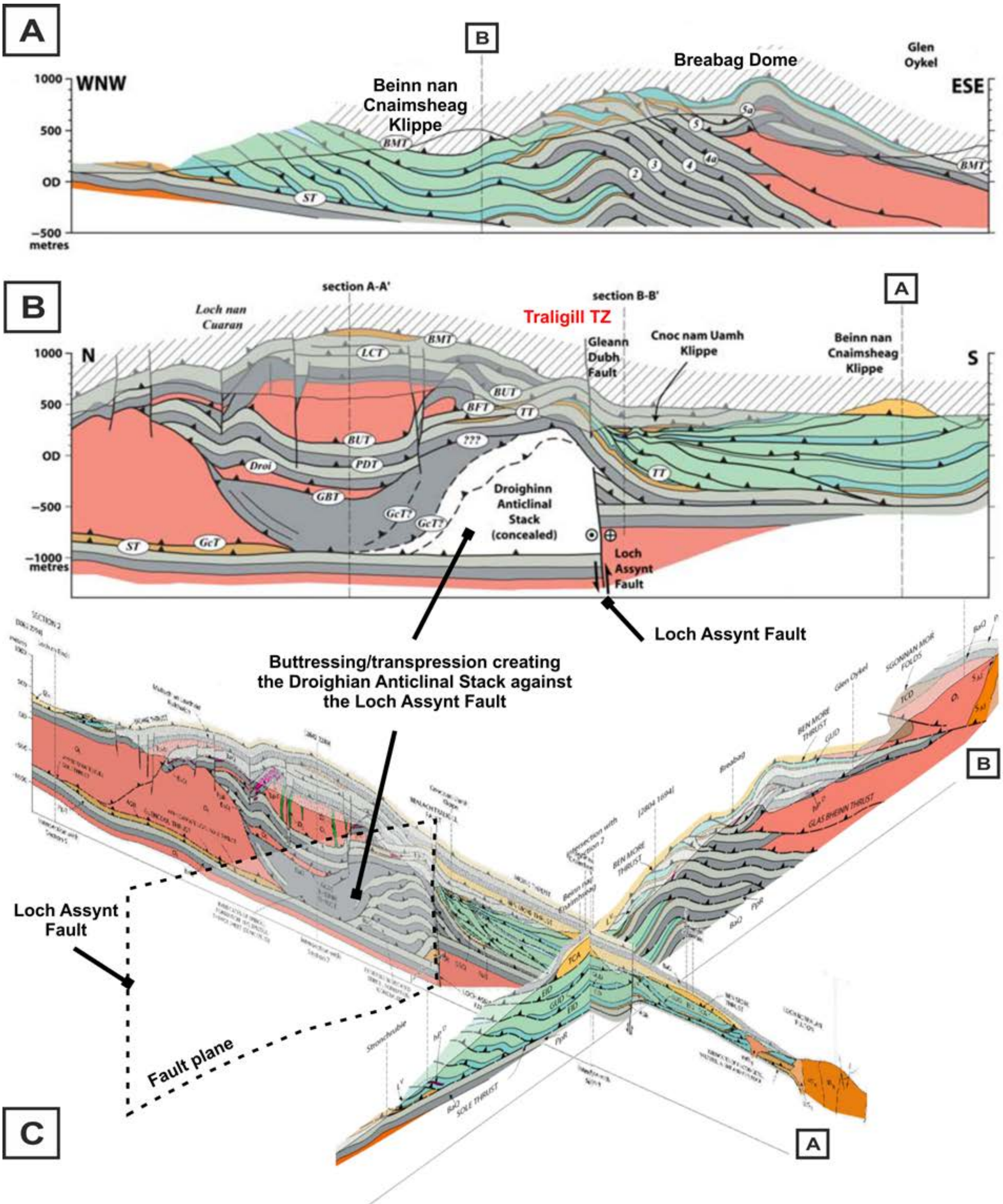


Figure 3.13: (A) Transport-parallel cross-section across the Breabag-Stronchrubbie system, southern wall of the Traligill Transverse Zone indicating structures developed through buttressing and/or transpression within the transport direction (e.g., Beabag Dome and Beinn nan Cnaimsheag Klippe). **(B)** Transport-lateral cross-section across the Traligill Transverse Zone identifying along-strike buttressing and/or transpression (e.g., the Droighinn Anticlinal Stack). **(C)** Fence diagram allowing the pseudo-three-dimensional properties along-strike to be identified and analysed. Locations of individual cross-sections are highlighted. (Adapted after Krabbendam & Leslie, 2010).

Transport-lateral (strike-parallel) cross-sections in theory cannot be balanced and restored due to unknown amounts of material laterally entering and leaving the section, whilst restorations of transport-parallel sections can only be balanced if the order of thrust propagation is determined (e.g., Dahlstrom, 1969; Marshak & Woodward, 1988). However, analyses of transport-parallel and transport-lateral cross-sections constrained by geometrical and kinematic data are admissible within transverse zone research (Paulsen & Marshak, 1998).

Constructions of transport-parallel and transport-lateral cross-sections within transverse zone settings allow the production of fence diagrams whereby pseudo-three-dimensional properties of cross-strike linkages and cross-strike discontinues may be viewed and placed within a three-dimensional along-strike context (e.g., Snedden & Spang, 1989, 1990; Wilkerson, 1992; Krabbendam & Leslie, 2010). Utilisation of transport-parallel and transport-lateral cross-sections for fence diagram production can be seen within the Traligill Transverse Zone, Assynt Culmination, Moine Thrust Zone, Scotland (e.g., Krabbendam & Leslie, 2010; Figure 3.13c). Advantages and disadvantages of cross-section construction are summarised within Table 3.8.

3.1.2.4. <u>Palinspastic restorations and / or reconstructions</u>

Determining sequences of thrust fault development within a thrust system is an important parameter needed for interpretations of both geometrical and kinematic evolution of a thrust belt (Butler, 1987; McClay, 1992). It is also essential for construction of balanced and restored cross-sections (e.g., Boyer & Elliott, 1982; Suppe, 1985; Butler, 1987; Morley, 1988; Woodward *et al*., 1989; Boyer, 1990). Section restoration or palinspastic restoration is a technique used to progressively restore a geological cross-section in an attempt to validate interpretations used to build the section. It is also used to provide insights into the geometry of earlier stages of geological development of an area (e.g., Thomas, 2007; Masini *et al*., 2010; Judge & Allmendinger, 2011 and references therein). However, it is fundamentally important to restore all strains and displacements in the reverse order to that in which they were applied (Butler, 1987).

Cross-section restorations therefore require detailed field studies to determine the order of thrust propagation and to identify forward propagating thrusts (i.e., foreland-propagating thrusts) and hindward propagating thrusts (i.e., out-of-sequence thrusts, Coward, 1984; Butler, 1987; Morley, 1988; Woodward *et al*., 1989; McClay, 1992). Out-of-sequence thrusts are caused by reactivation of older in-sequence thrusts or by development of new thrust faults through a deformed thrust sheet (Morley, 1988; DeCelles *et al*., 2001; Alcicek & ten Veen, 2008). Cross-sections which can be successfully undeformed to a geologically reasonable geometry, without change in area, are known as balanced sections (Dahlstrom, 1969; Thomas, 2007).

Balancing is a geometrical technique applied in either two or three dimensions. In many published examples, two dimensions are used where it is assumed that the section is parallel to the transport direction and area is maintained during deformation and displacements of the rock volume (Dahlstrom, 1969; 1990; Hossack, 1979). Comparably, a palinspastic map is a map-view of geological features representing the state before deformation (Brewer, 2004; Cook, 2010). Within cross-strike discontinuity studies, palinspastic restoration of geological cross-sections have been used to create palinspastic maps to identify along-strike pre-, syn- and / or post-depositional basement faults, lateral ramps and displacement-transfer zones within the pre-thrust template. Primary studies have focused within regions displaying well documented and constrained tectono-stratigraphical sequences such as the Bessemer, Harpersville, Anniston and Rising Fawn transverse zones within the southern Appalachian thrust belt (e.g., Thomas & Bayona, 2002; Brewer, 2004; Cook, 2010). Advantages and disadvantages are identified within Table 3.8.

Cross-section construction, Palinspastic restorations and reconstructions		
	Advantages	**Disadvantages**
Cross-section construction	• Visualisation of along-strike changes in geometries and stratigraphical thicknesses based on map-trends. • Determinations of thrust sequences of propagation • Allow quantitative prediction of the subsurface architecture even where no seismic data available	• Time consuming to construct and must be constrained against geometrical rules of development to allow balancing techniques (e.g. Suppe, 1985) • Cross-sections are interpretations of map data and are only as good as the initial information (Woodward *et al*., 1989
Palinspastic restorations/ reconstructions	• Needed for the balancing and restorations of cross-section constructions • Identification of along-strike compartmentalisations created as a result of pre-thrust template irregularities (i.e. basement faults)	• Linking of sections along-strike implicitly assumes deformation is restricted to planes parallel to each section • Require a series of detailed cross-sections within well constrain tectono-stratigraphical units which are not always possible

Table 3.8: The advantages and disadvantages of cross-section construction and palinspastic restorations/reconstructions within cross-strike discontinuity studies

3.1.3. 2D and / or 3D modelling techniques

Analogue modelling is a technique in which artificial and / or laboratory materials are employed to simulate the mechanical behaviour of deforming rocks in nature. Analogue modelling of crustal deformation is geometrically, kinematically and dynamically similar to that in nature if experimental models and natural systems are characterised by a similar distribution of stress, densities and rheology (Konstantinovskaya *et al*., 2007 and references therein). Experiments are commonly conducted under normal gravity conditions using generally two types of materials to mimic rheological changes with depth and along-strike: frictional materials (e.g., dry, non-cohesive quartz), to simulate the brittle (Coulomb-Mohr) behaviour of upper crustal rocks; and viscous materials (e.g., different types of silicone putties, plasticine, or aluminium microspheres,) to simulate deeper ductile rock units (Konstantinovskaya *et al*., 2007). Such models have been used for the Apennines (Italy), the southern Pyrenees, the Pindos (Greece) and the West Spitsbergen / Greenland fold-thrust belts (Bigi *et al*., 2009 and references therein).

Analogue modelling has been identified by many studies to be a valuable tool for studying the evolution of orogenic wedge development along pre-thrust templates commonly using constant thickness sand packs both in two and three dimensions (e.g., McClay, 1989; Malavieille *et al*., 1991; Storti *et al*., 2000; Mouthereau *et al*., 2002; McClay *et al*., 2004; Mattioni *et al*., 2007; Bigi *et al*., 2009; Noble & Dixon, 2011; Figure 3.14). Sand box models, using simple along-strike tapering geometries, have highlighted that thrust

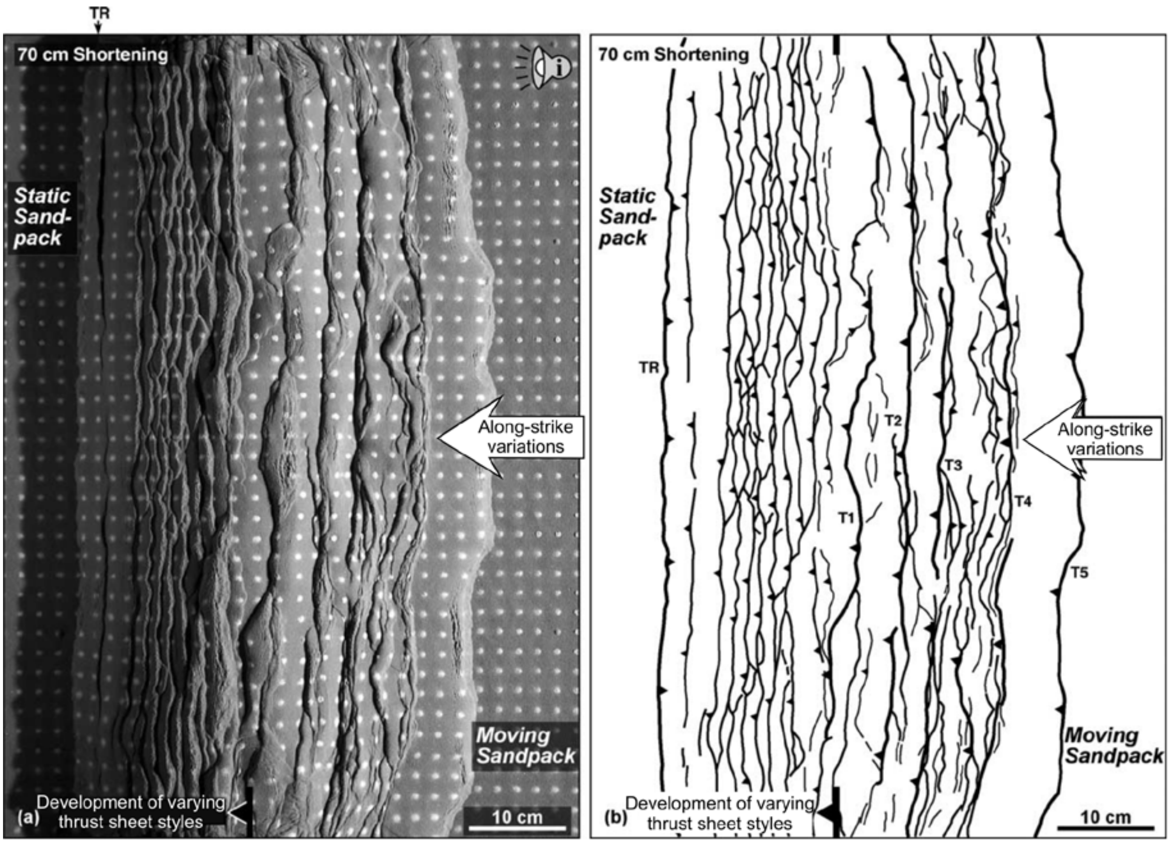
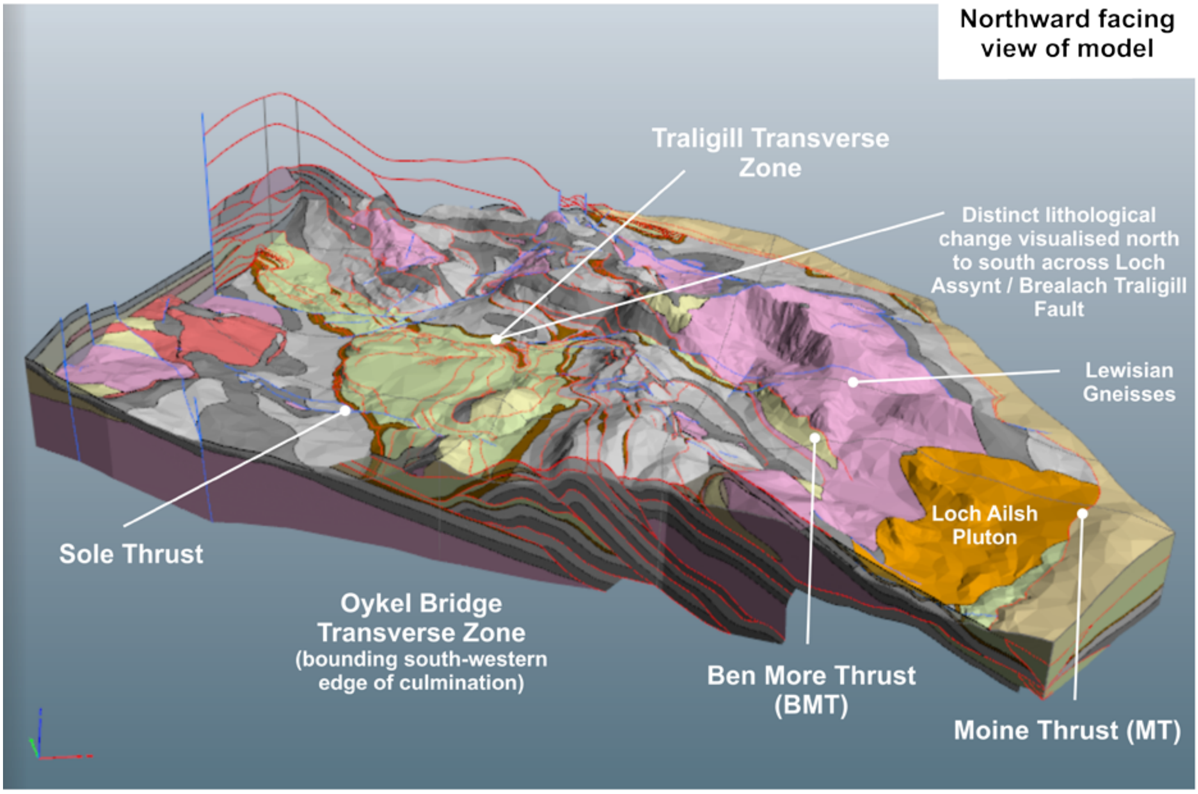


Figure 3.14: Analogue model showing along-strike variations in thrust style as a result of oblique convergence and along-strike transpression/transtension. Such models developed over differing pre-thrust templates allow cross-strike discontinuities to be determined (McClay *et al*., 2004)

wedges accreting from pre-orogenic tapering sedimentary series evolve in a non-cylindrical fashion, and that thickness variations play a first-order role in determining the three-dimensional architecture of resulting orogenic belts (McClay *et al*., 2004; Bigi *et al*., 2009 and references therein, Figure 3.14).

Lateral ramps, cross-strike discontinuities and transverse zones have been modelled using sand boxes (e.g., Calassou *et al*., 1993, McClay *et al*., 2004; Figure 3.14) and numerically (Wilkerson *et al*., 1991; Mookerjee & Mitra, 2009) to determine the evolution of cross-strike phenomena and kinematic linkages. Three-dimensional visualisations of thrust and fold geometries have also been computed but have not been fully interpreted widely over transverse zones (e.g., Wilkerson *et al*., 1991; Marshak *et al*., 1992; Price, 2001; Hinsch *et al*., 2002; Massoli *et al*., 2006; Gorney *et al*., 2007; Noble & Dixon, 2011; Pastor-Galan *et al*., 2012).

However, several studies have sought to rectify this paucity within cross-strike discontinuity and transverse zone research. A three-dimensional model produced depicting the development of the Assynt Culmination within the Moine Thrust Zone, NW Highlands, Scotland (Figure 3.15), allows the visualisation and analysis of the development of the Traligill Transverse Zone along-strike. A clear northward stratigraphical change occurs across the Loch Assynt / Brealach Traligill Fault, as a result of buttressing and / or transpression along a one hundred metre step in basement. Construction of this three-dimensional model was achieved through detailed field observations and transport-parallel / transport-lateral cross-section constructions (e.g., Leslie *et al*., 2012, 2013; Figure 3.15). Advantages and disadvantages of modelling techniques are identified within Table 2.9.



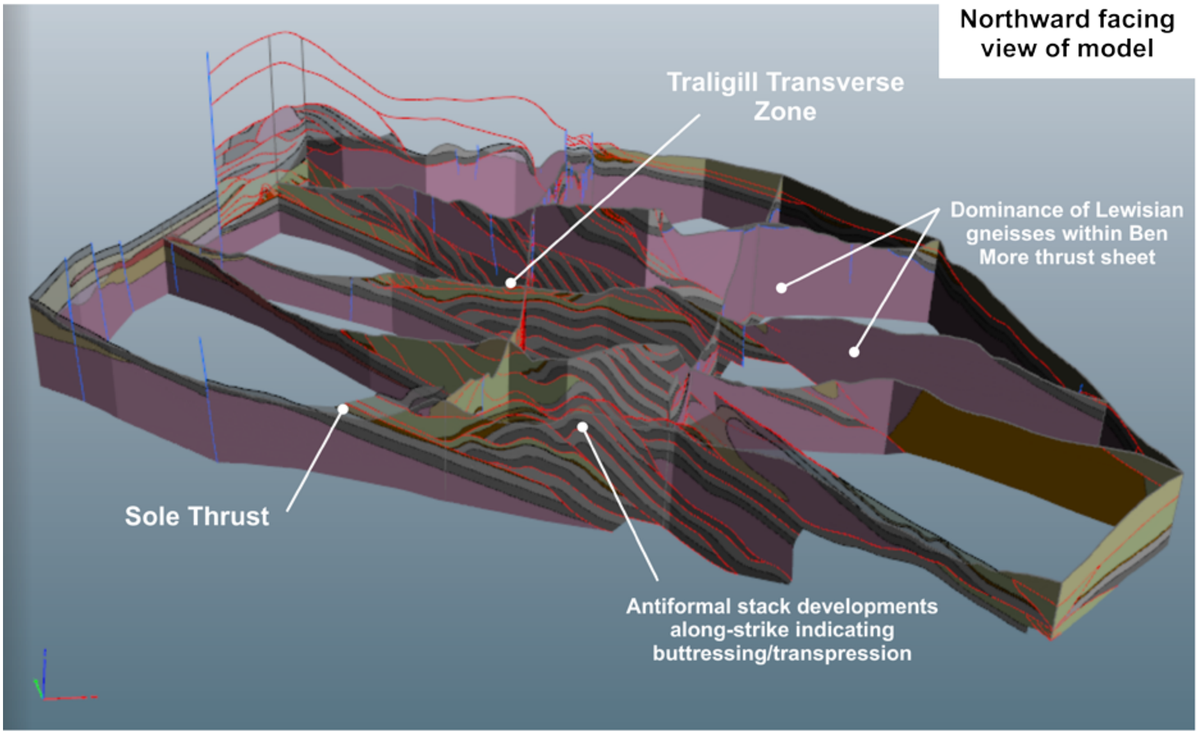


Figure 3.15: Three-dimensional geological model of the Assynt Culmination, NW Highlands, Scotland **(A)**. Production of the geological model from transport-parallel and transport-lateral cross-sections **(B)** allows the analysis of both map-view surface expressions and subsurface causal structures within the Traligill Transverse Zone and the Assynt Culmination as a whole (Adapted after British Geological Survey, 2012).

2D and / or 3D modelling techniques	
Advantages	**Disadvantages**
• Allow the determination and visualisation of structural developments along-strike • Allow geological modelling of poorly imaged structures • Visualisation of interpreted model within three-dimensions at different temporal and spatial scales during development	• Timely to construct and implement • Incapable to thoroughly reproduce the thermo-mechanical properties of natural rocks

Table 3.9: The advantages and disadvantages of modelling techniques within cross-strike discontinuity studies

3.2. New methodology development: Fault network architectural analysis

Previous techniques used for the identification of cross-strike discontinuities have distinct limitations within their application. Identification techniques such as gravimetric and aeromagnetic surveys, seismic reflection / refraction surveys and well-log data sets are costly to implement and sparsely utilised. Commonly, utilisation of these techniques is restricted to regions with economic importance (i.e., hydrocarbon exploration and extraction), such as, the Appalachians and Zagros fold-thrust belts (e.g., Brewer, 2004; Goffey *et al*., 2010; Burberry *et al*., 2011). As such, further restrictions placed on the use of these data sets may also be present due to data protection. Analyses associated with the constrains of gravity, seismic and well-log data sets, such as structural contour mapping and isopach analyses are therefore not always applicable within all cross-strike discontinuity identification studies. Within this research, no seismic, gravimetric or aeromagnetic data sets are available and as such are not utilised.

Furthermore, studies incorporating provenance analyses and stratigraphical correlations are only required within regional studies containing poorly understood stratigraphical frameworks, something not applicable within all fold-thrust belts, such as the well constrained Moine and Cantabrian thrust belts. These techniques, similar to previously stated techniques, are costly to implement and require specific types of lithology to determine along-strike variations in structural trends. Consequently, provenance and stratigraphical correlations are not implemented within this study.

Techniques utilised for determining along-strike architectural variations are commonly implemented over a variety of scales to good effect. Techniques such as stratigraphical separation diagrams, geological map analyses and / or re-mapping, cross-section construction and collection of geometrical and / or kinematic data sets form a prerequisite cornerstone within cross-strike discontinuity research studies globally. However, within architectural analyses of cross-strike discontinuities, localised detailed field studies commonly focus on individual structural development of faults and folds, or specific regions or structures, and therefore commonly overlook relationships between regional and localised structural developments and vice versa. Few studies have developed and implemented techniques which can be utilised within any fold-thrust belt to identify thrust ramps and cross-strike discontinuities from a regional- to localised-scale and to the thrust belt as a whole. Furthermore, spatial distribution analyses of architectural components, such as branch-lines, fault-tip lines and fault cut-off points, have not been widely implement within cross-strike discontinuity studies.

Therefore, development of a new cross-strike discontinuity identification methodology, which can be implemented within any fold-thrust belt setting to bridge the gap between regional identification analyses, incorporating thrust ramp identifications and classifications, and detailed local-scale field studies, to determine spatial distributions and architectural components of cross-strike discontinuities, is therefore justified within this research.

New cross-strike discontinuity (CSD) identification methodologies have been developed to identify transverse zones on regional and localised spatial scale. These methods include fault network analyses incorporating:

- Thrust ramp colour coding classifications
- Branch-line analyses
- Fault-tip line analyses
- Cut-off point analyses

Regional analyses of the interplay of different structural components within thrust systems, (i.e., the fault network) have been utilised within this research to analyse along-strike compartmentalisation and terminations of structures within transverse zones and the thrust belt as a whole, including along-strike variations in structural style (e.g., folding versus faulting-dominant domains: Kley *et al*., 1999; Giambiagi *et al*., 2008); along-strike identifications of thrust ramps (which in turn are classified defendant on alignment with regard to regional thrust translation), and determination of spatial distributions and architectural components of cross-strike discontinuities and cross-strike linkages. Branch-line, fault-tip line and cut-off point analyses determine thrust nucleation, propagation, termination and stratigraphical décollement relationships along-strike plus cross-strike linkages within transverse zones.

The following subsections describe the new methodology for identifying and geometrically analysing cross-strike discontinuities (CSDs) and transverse zones within regional-scale thrust architectural analyses. These new methods have been tested within the Bessemer Transverse Zone, southern Appalachian Thrust Belt, Alabama, USA, within a structure known as 'The Knot' to determine implications and the advantages and / or disadvantages of the new methodology prior to application within the Moine and Cantabrian thrust belts.

3.2.1. Thrust ramp coding classification

New colour coding methodologies, developed within this work, were undertaken to identify thrust footwall / hanging-wall ramps and stratigraphical flats along-strike within the thrust sequence. Ramp characteristics and orientations in regard to regional transport directions are also established within the methodology coevally with kinematic analyses. Where thrusts can be seen laterally climbing up- or down-stratigraphical section within stratigraphical cut-off analyses, frontal, lateral or oblique ramps may be identified depending on alignments to regional transport (e.g., Thomas, 1990). These are colour coded depending on whether ramps occur in the footwall or hanging-wall. Similarly identifications are undertaken for stratigraphical hanging-wall and footwall flats within the sequence using the criteria shown in Figure 3.16. Ramps within map-traces are highlighted within the colour coding methodology with red and purple lines (hanging-wall and footwall respectively), whilst stratigraphical flats are highlighted by green and yellow lines (hanging-wall and footwall respectively).

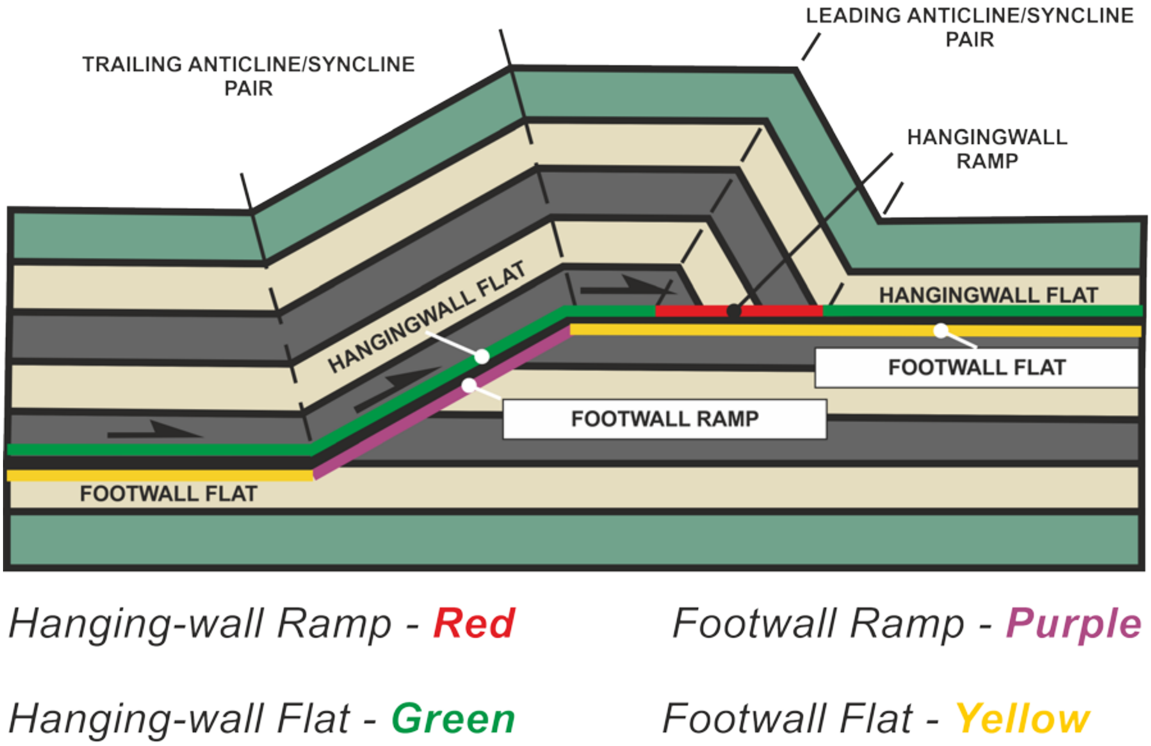


Figure 3.16: Thrust ramps in cross-section depicting the different classifications of flats and ramps within the footwall and hanging-wall. New colour coding methodology is utilised to demonstrate these relationships for along-strike thrust ramp classifications.

Thrust lateral stratigraphical climb within hanging-wall and footwall thrust ramps and flats and along-strike variations in thrust style have been determined. Frontal hanging-wall ramps generally create long ramp profiles and are orientated ~90° to regional transport, whereas lateral hanging-wall ramps are generally short and are aligned sub-parallel to the regional transport direction (Figure 3.17; 3.18a). Lateral ramp expressions are identified within the hanging-wall over lateral and frontal ramp intersections or within the footwall during thrust translation over transport sub-parallel basement structures (Figure 3.18b). Numerous frontal ramp map-view expressions are identified along-strike including: stratigraphical flat-on-flat geometries (Figure 3.19a); hanging-wall ramp / footwall flats (Figure 3.19b); hanging-wall flat / footwall ramp geometries (Figure 3.19c); and hanging-wall / footwall ramp-on-ramp geometries (Figure 3.19d).

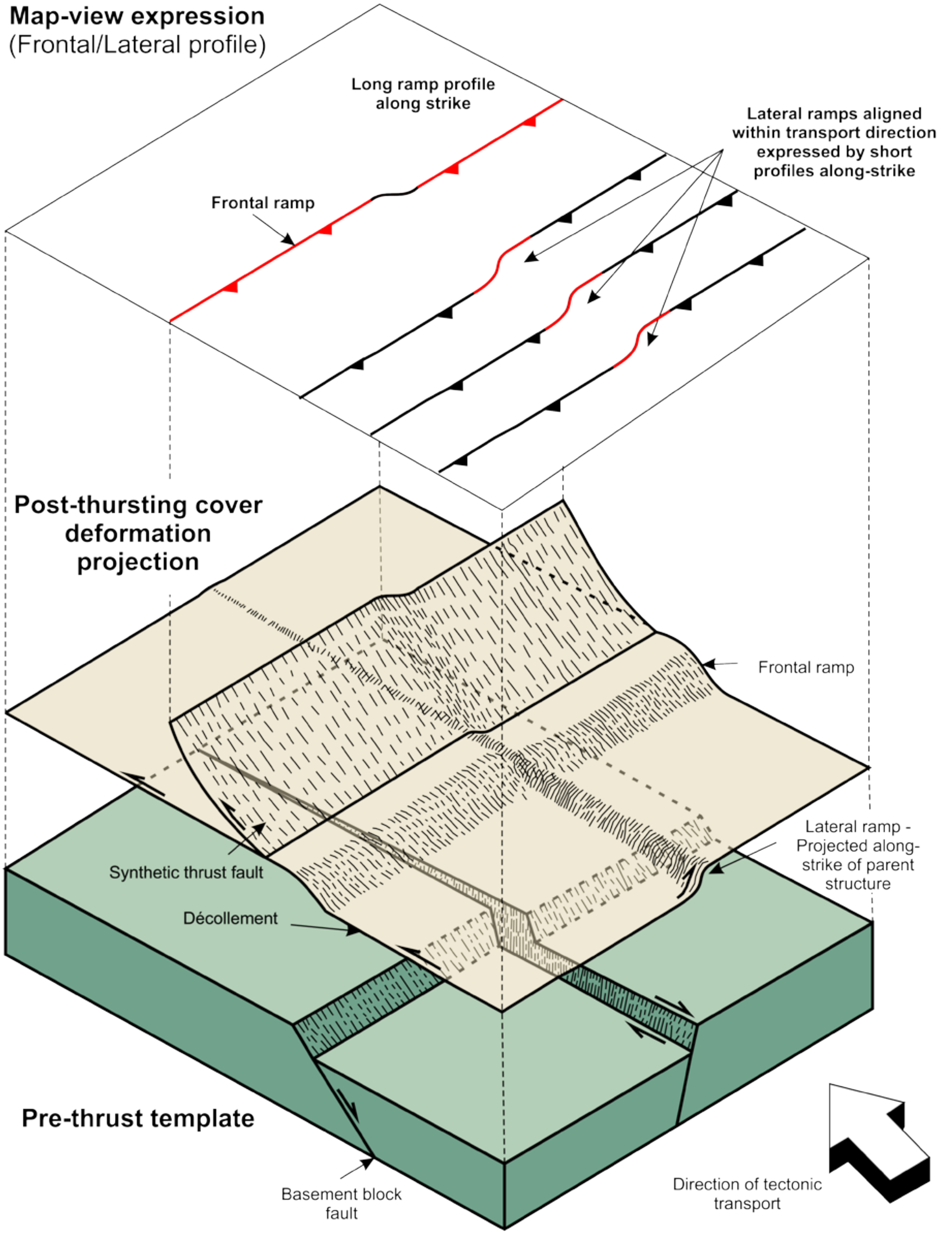
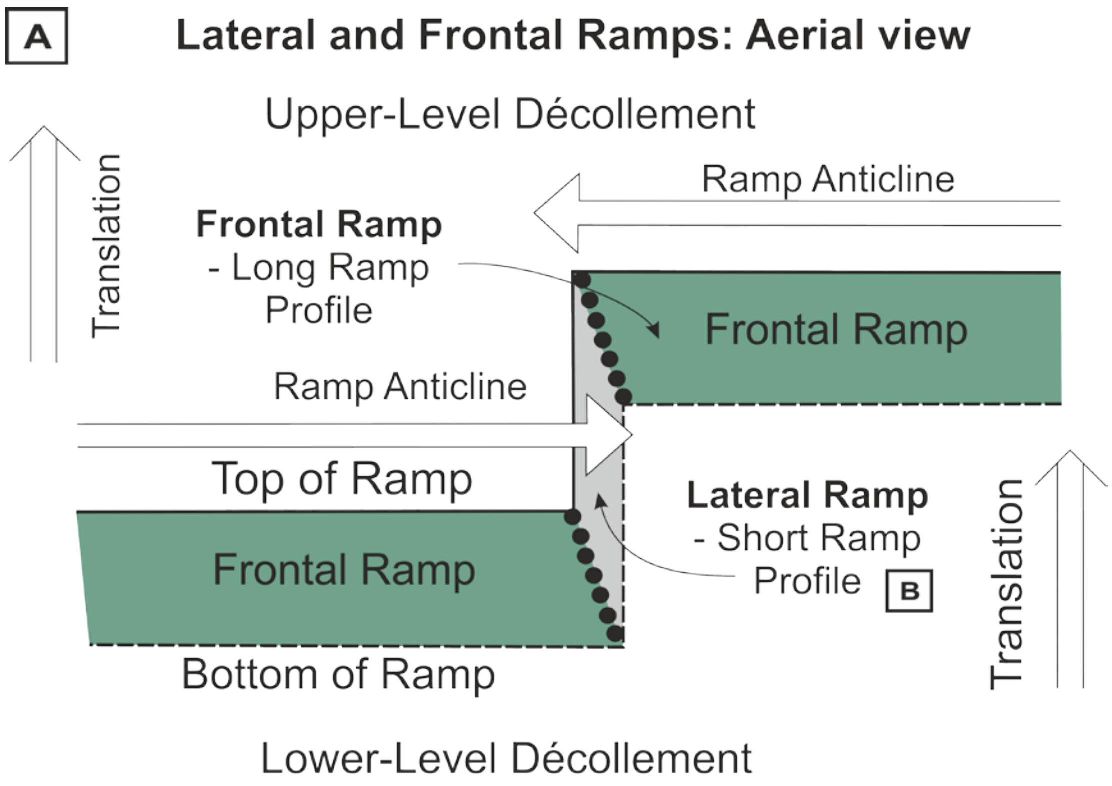


Figure 3.17: Block diagram showing relationship between basement block faults, frontal ramps, basement cross-strike faults and lateral ramps. Final post-thrusting projections of cover deformation structures and their map-view expression are also illustrated highlighting along-strike variations in profile length. Frontal ramps produce long along-strike profiles, whilst lateral ramps produce short along-strike profiles.



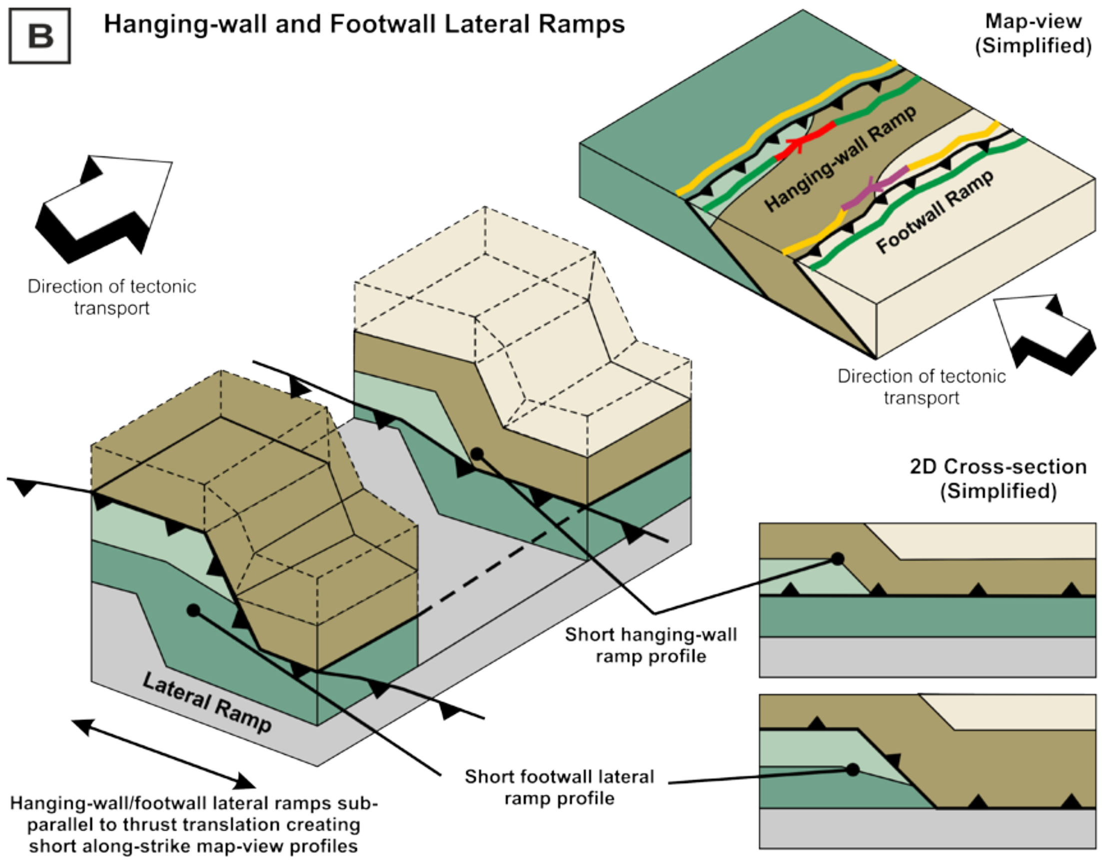


Figure 3.18: **(A)** Frontal and lateral ramp traces in aerial view (Adapted after Thomas, 1990). Thrust translation over lateral ramps seen within (A) will produce short ramp profiles along-strike within the colour coding analysis. **(B)** Three-dimensional synthetic block models demonstrating transport-parallel variations along lateral ramps within the hanging-wall and footwall creating short profiles in map-view within the new colour coding methodology. Thrust facing within map-view is also illustrated.

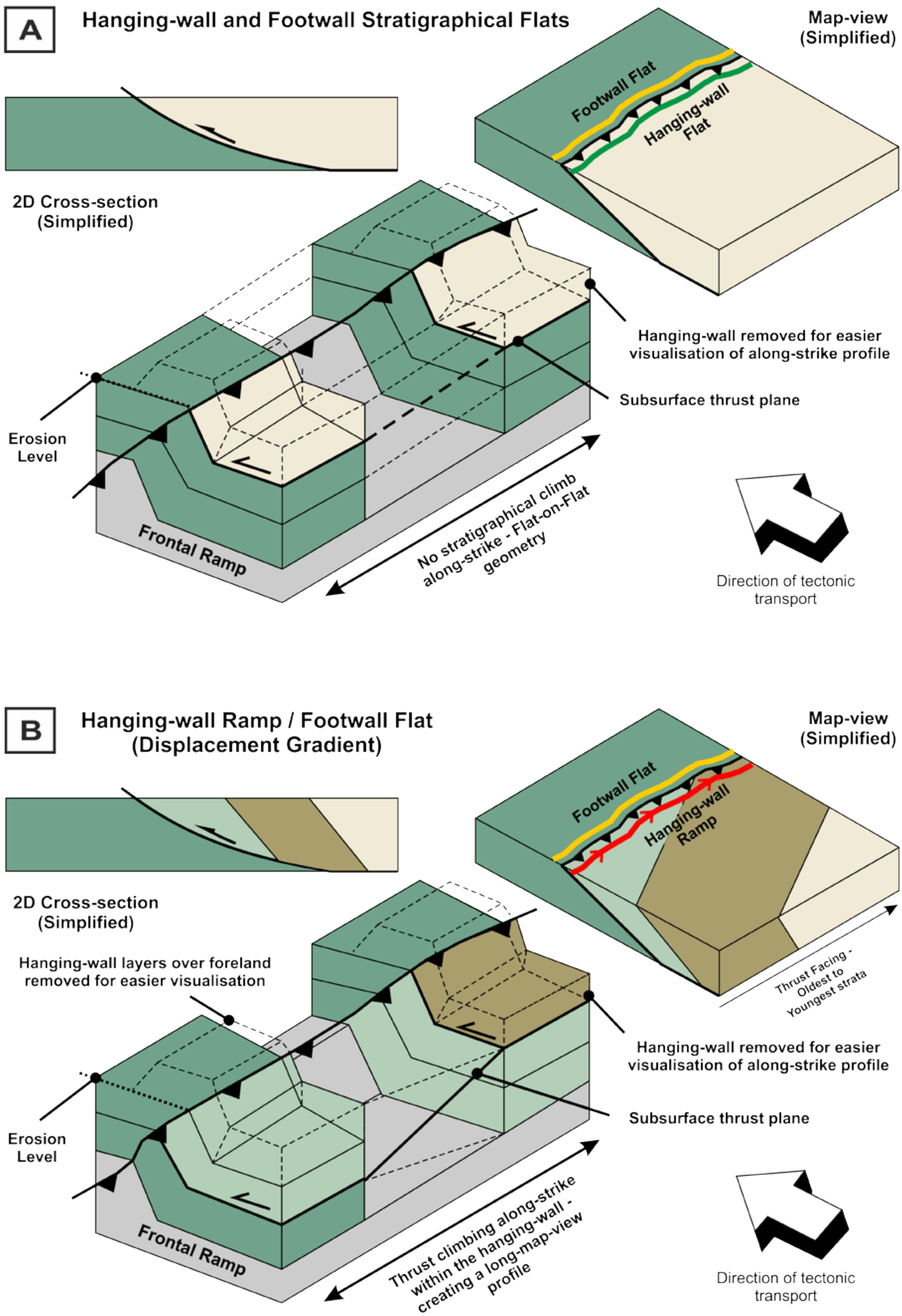
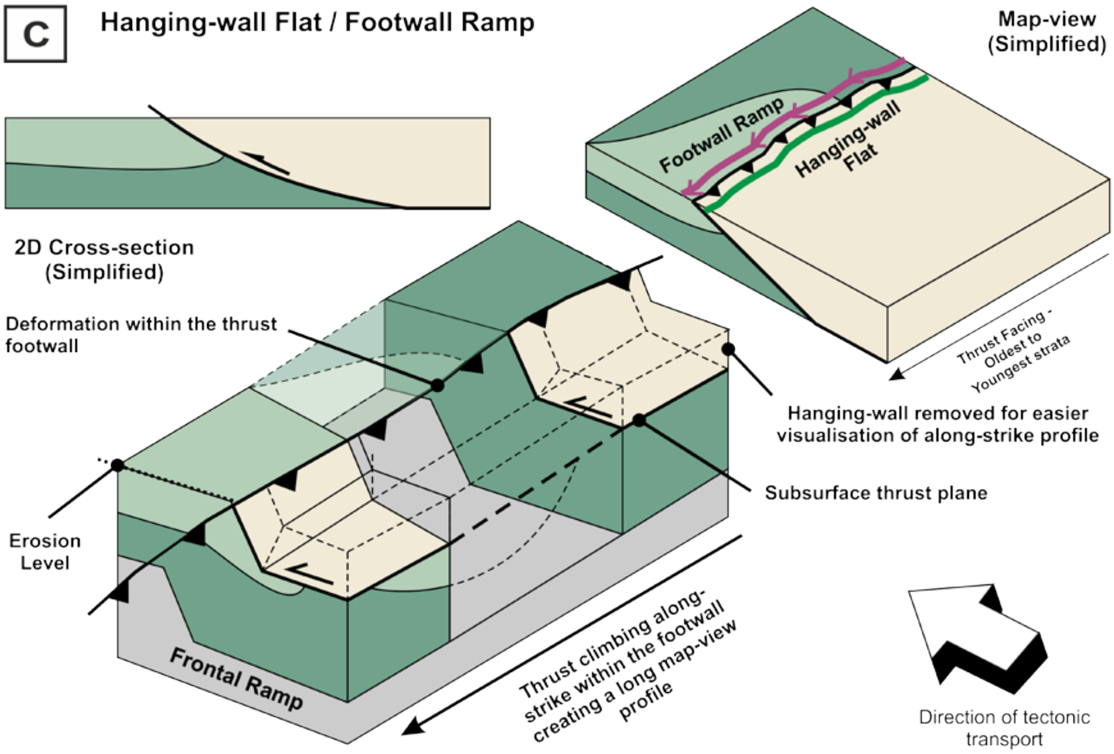


Figure 3.19: Three-dimensional synthetic block models demonstrating along-strike variations over frontal ramps. **(A)** Stratigraphical flat-on-flat geometry highlighting no lateral thrust climb along-strike. **(B)** Hanging-wall ramp/footwall flat geometry indicating a lateral climb along-strike within the hanging-wall strata. Thrust facing within the hanging-wall strata is also demonstrated. Both examples create long frontal profiles along-strike within the new colour coding methodology.



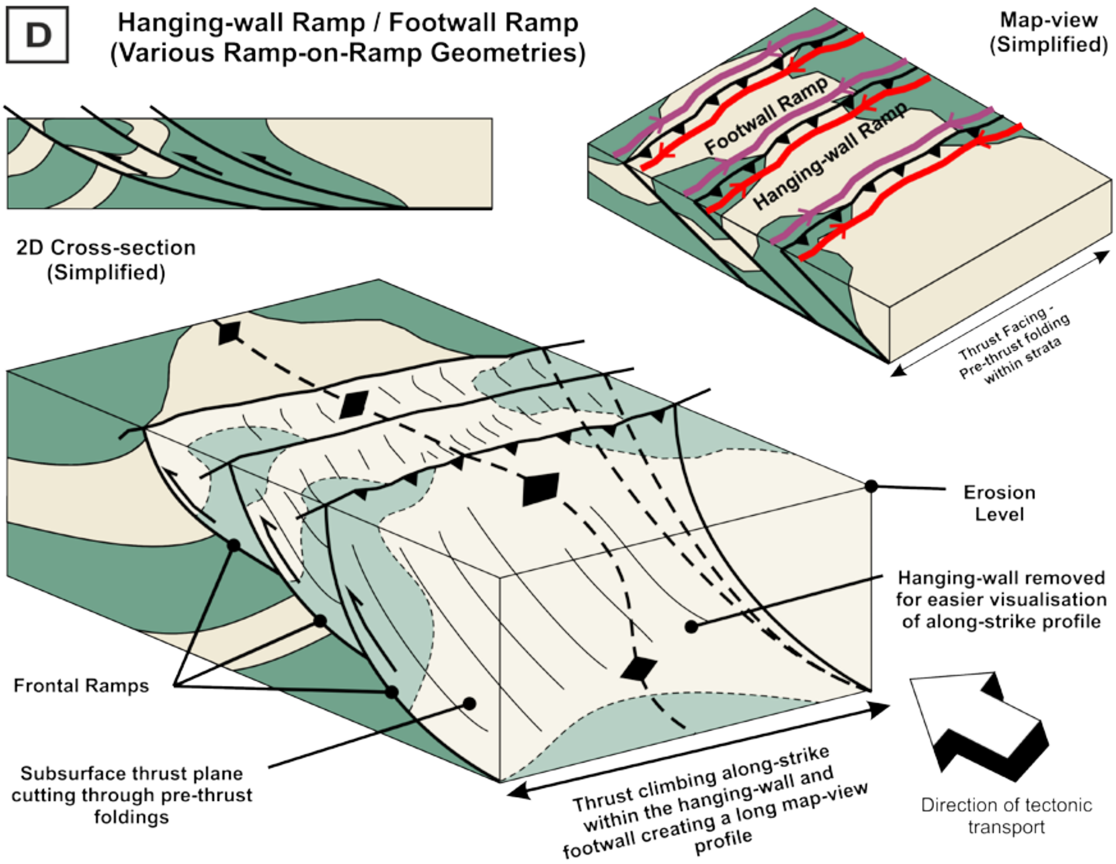


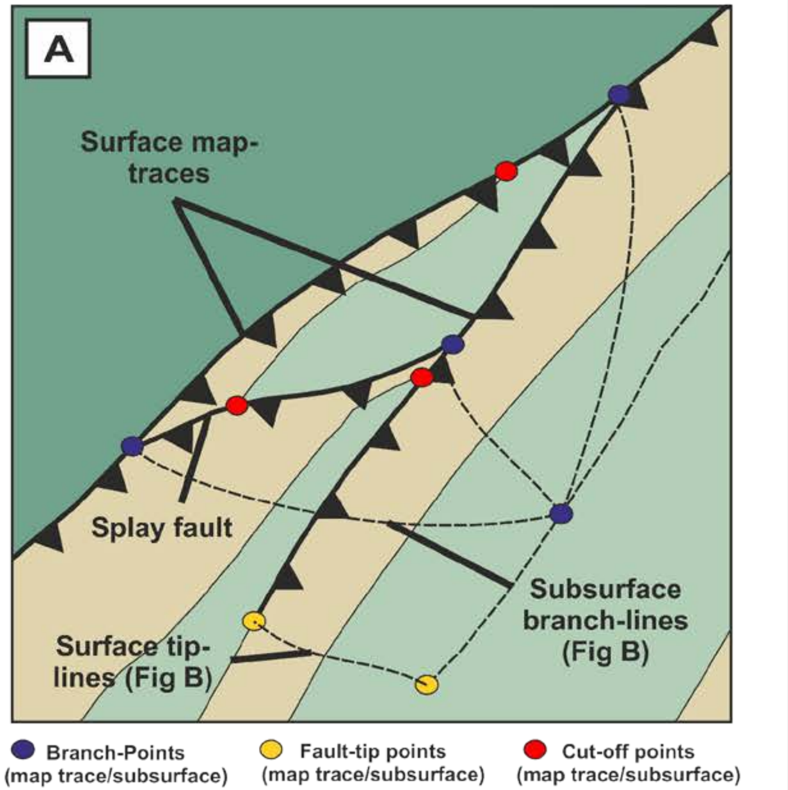
Figure 3.19...cont: Three-dimensional synthetic block models demonstrating along-strike variations over frontal ramps. **(C)** Hanging-wall flat/footwall ramp geometry highlighting lateral thrust climb along-strike within the footwall as a result of pre-thrust folding or footwall deformation during thrust propagation. **(D)** Hanging-wall ramp/footwall ramp geometries indicating a lateral climb along-strike within the hanging-wall and footwall strata. Along-strike thrust facing is also demonstrated. Both examples create long frontal profiles along-strike within the new colour coding methodology.

Thrust facing (i.e., direction of stratigraphical climb of the ramp), is represented as an arrow head within the hanging-wall and footwall ramp sequences (Figure 3.18; 3.19). Ramps laterally climbing up- or down-stratigraphical section within the thrust sequence (i.e., lateral ramps), may signify basement-related lateral structures within the footwall of the allochthon when more than one short lateral ramp is aligned within the regional thrust translation direction (Figure 3.17; 3.19). Alignments along-strike of such structures can be verified using stratigraphical separation diagrams, as well as, localised geometrical and kinematic data.

3.2.2. Branch-line analyses

Thrust linkages and lateral connectors have been used to test Thomas's (1990) statement that cross-strike linkages within transverse zones have abrupt (rather than gradual) terminations along-strike, which can be identified over a range of map-scales, types and offsets. Alignments of branch-points within the transport direction during fault network analyses are just one method by which cross-strike linkages and subsurface irregularities within the pre-thrust template can be established within transverse zones.

The term 'branch-line' was initially described as the line of intersection between a trailing thrust and leading thrust, or the line of intersection between two thrust sheets (Boyer & Elliott, 1982; McClay, 1992). Conversely, branch-points are interpreted as the point of intersection between a branch-line and the map-view erosional surface (Figure 3.20). Erosion through a tip or branch-line produces the tip and branch-points shown on maps. Branch-lines are recognised as displacement transfer cross-strike linkages where displacement is transferred from one thrust to another along-strike and are represented by blue points in map-view (Figure 3.20).



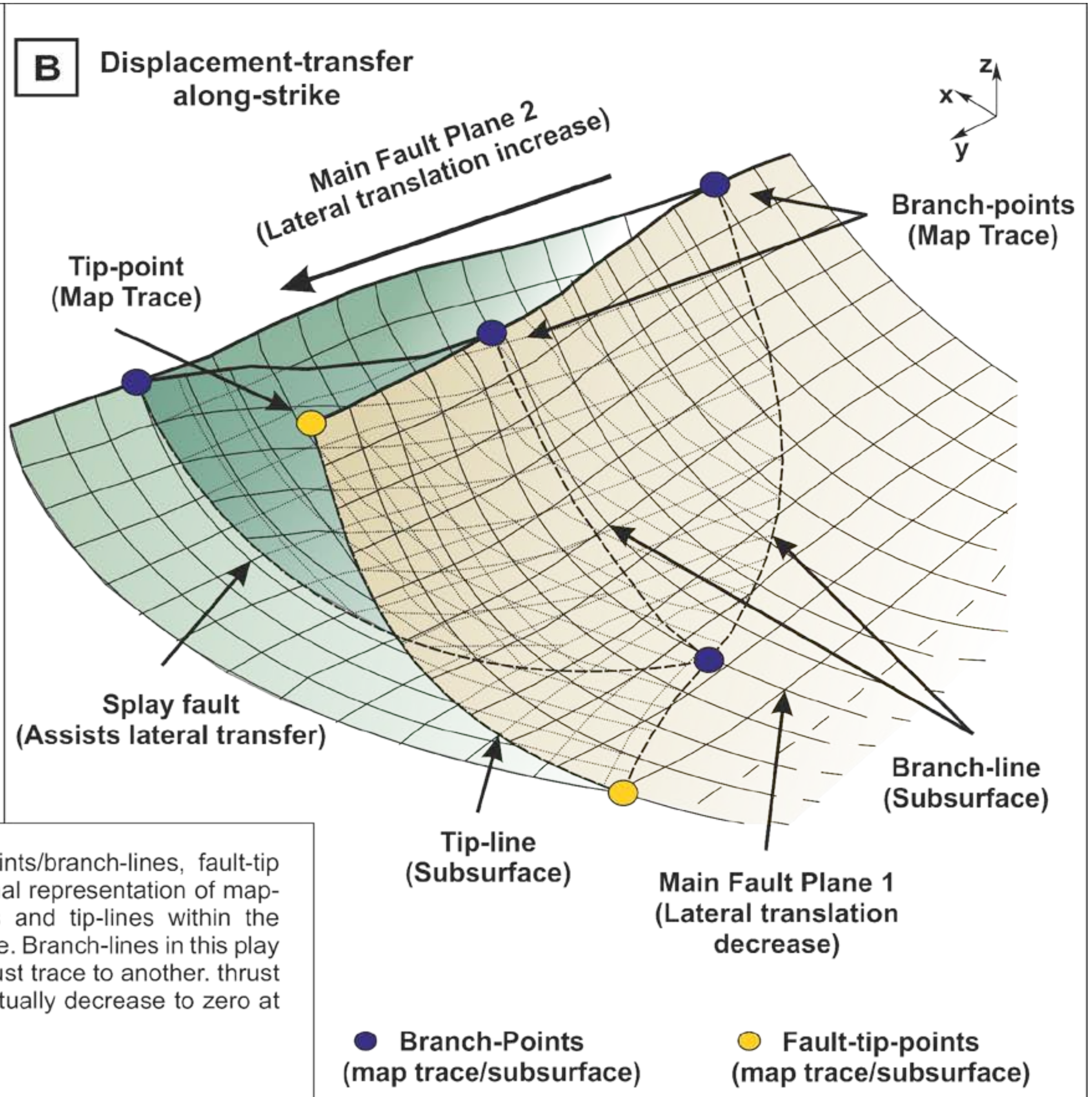


Figure 3.20: **(A)** Two-dimensional (map-view) analysis of branch-points/branch-lines, fault-tip points/fault-tip lines and cut-off points/cut-off lines. **(B)** Three-dimensional representation of map-view seen in (A). Figure demonstrates the interplay of branch-lines and tip-lines within the subsurface, as well as, expressing the two-dimensional surface fault trace. Branch-lines in this play represent zones where displacement is transferred laterally from one trust trace to another. thrust traces that experience along-strike reductions in thrust translation eventually decrease to zero at fault-tip lines.

Thrust branches occur as a result of a change in structural detachment within the stratigraphical profile along-strike, changes in stratigraphical thickness or lithofacies, or lateral decreases in thrust displacement. Along-strike variations may occur abruptly over large, steep basement-related structures which have short wavelength profiles, but high amplitudes along-strike, or gradually over several kilometres. Gradual changes along-strike may occur where amplitudes of the potential basement-related structure are lower and structural wavelength is longer, creating branch-lines along-strike within the fault network along-strike profile (Figure 3.21a).

Alignments of branch-points and branch-lines parallel to thrust transport direction within the fault network is indicative of along-strike displacement transfer over transverse structures within the pre-thrust template (Figure 3.21a). Cross-strike linkages which occur gradually or abruptly are key for determining, not only the geometrical and kinematic development of transverse zones, but also compartmentalisation of the thrust belt as a whole (e.g., McCaig & McClelland, 1992; Allerton, 1998). These can be determined through architectural analyses of cross-strike linkages. Branch-line analyses using geological maps are complemented by along-strike stratigraphical separation applications along fault traces.

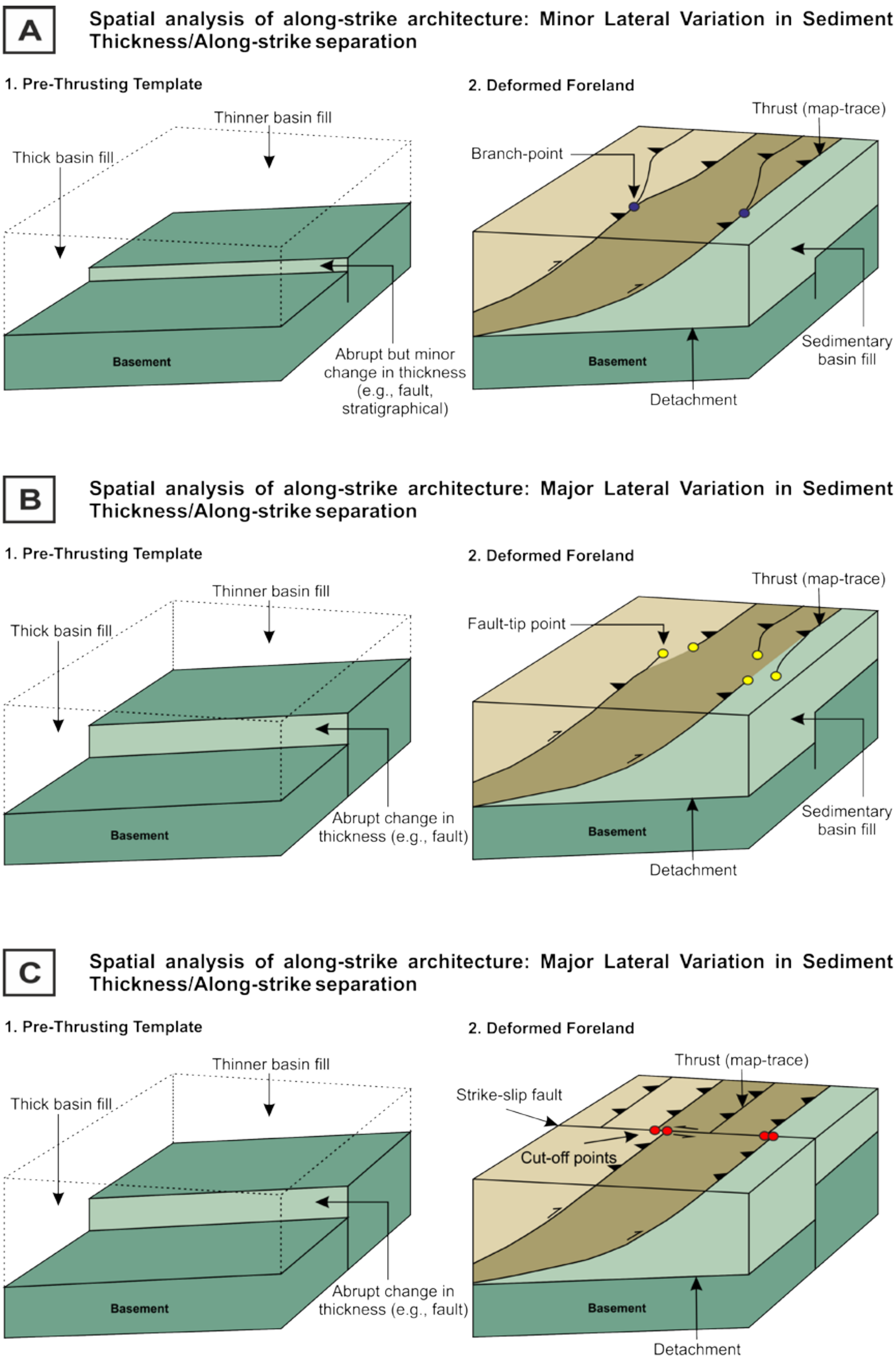


Figure 3.21: Impact of along-strike changes in sediment thickness and separation on thrust architecture: **(A)** Abrupt but small change along-strike change across a pre-existing fault zone or stratigraphical thickness causing a gradual kink or branching of superimposed thrusts along-strike without the necessity for fault reactivation; **(B)** Abrupt and substantial lateral change across a pre-existing fault zone or stratigraphical thickness, causing either thrust nucleations or terminations within map-view profiles; **(C)** Abrupt and substantial lateral change across a major pre-existing fault zone, resulting in fault reactivation, along-strike displacements of strata and lateral partitioning of the thrust belt.

3.2.3. Fault-tip line analyses

Fault-tip line analyses have been used to identify along-strike terminations of fault traces along and / or against potential sub-décollement transverse structures. Fault-tip lines are described as a line within the subsurface denoting a point at the end of a fault-trace on a map, beyond which displacement is zero (Boyer & Elliott, 1982). Fault tip points are regarded as the one-dimensional map-view expression of fault-tip lines (Figure 3.20). At lateral fault-tip lines, total thrust displacement (i.e., displacement of the lowest hanging-wall cut-off) reduces to zero. Structures observed within fault-tip regions should therefore represent the earliest stages of thrust development (e.g., Fischer & Woodward, 1992). Analyses of map-trace elements, such as fault-tip points within the fault network represent thrust terminations or nucleation points for lateral displacement within the thrust system.

Pre-thrust template architecture and / or stratigraphical controls within the fold-thrust belt as a whole can also be determined. Fault-tip points aligned within the thrust transport direction represent thrust-trace terminations against basement-related lateral structures within the pre-thrust template. Fault-trace terminations present an abrupt along-strike change in thrust architecture, rather than a gradual along-strike change (i.e., thrust branch-lines), and may be produced as a result of along-strike buttressing effects against pre-thrust basement structures and / or changes in thrust translation orientations locally. Fault-tip points are denoted within the fault network analyses with yellow points (Figure 3.20; 3.21b).

3.2.4. Cut-off point analyses

Along-strike terminations of stratigraphical interfaces against fault map-traces and dominant structures such as transverse (tear) faults are common in thrust belts (e.g., Turner *et al*., 2010). Cut-off lines are described as a line of intersection between a thrust surface and a stratigraphical interface within the subsurface, whilst cut-off points are regarded as the map-view expression of cut-off lines (Figure 3.20). A cut-off line could also be called an 'edge' because it indicates the intersection of two surfaces (e.g., Douglas, 1958; Boyer & Elliott, 1982; Coward, 1985; Diegel, 1986; McClay, 1992).

Within this work, map-trace cut-off points within the fault network indicate abrupt terminations along-strike at dominant structures rooted within the allochthon or autochthon which are sub-parallel to the thrust translation direction (i.e., transverse faults; Figure 3.21c). Compartmentalisation processes describe the movement of material laterally and transversely within transverse zones either during or subsequent to thrusting. Cut-off analyses are also undertaken to determine the degree of thrust map-trace stratigraphical climb laterally along-strike. Along-strike lithological terminations against fault-traces show thrust ramp and stratigraphical relationships. Furthermore, cut-off line analyses are used to determine thrust sequences, including 'out-of-sequence' thrust phases. These are presented by red points within the fault network analysis (Figure 3.20; 3.21c)

3.2.5. Case Example: 'The Knot', Bessemer Transverse Zone, Alabama, southern Appalachian Thrust Belt, USA

The southern Appalachian Thrust Belt within Alabama consists of Cambrian to Upper Carboniferous (Pennsylvanian) strata deformed by predominantly northeast-striking, northwest-translated thrust faults and thrust-related folds formed during the late Palaeozoic Alleghanian Orogeny, deforming the pre-existing Laurentian passive margin (Figure 3.22; Thomas & Neathery, 1980; Hatcher *et al*., 1989; Thomas & Bayona, 2005; Bayona & Thomas, 2006). Structural changes within these northeast-striking faults and fault related folds mark the areal distribution of transverse zones along-strike.

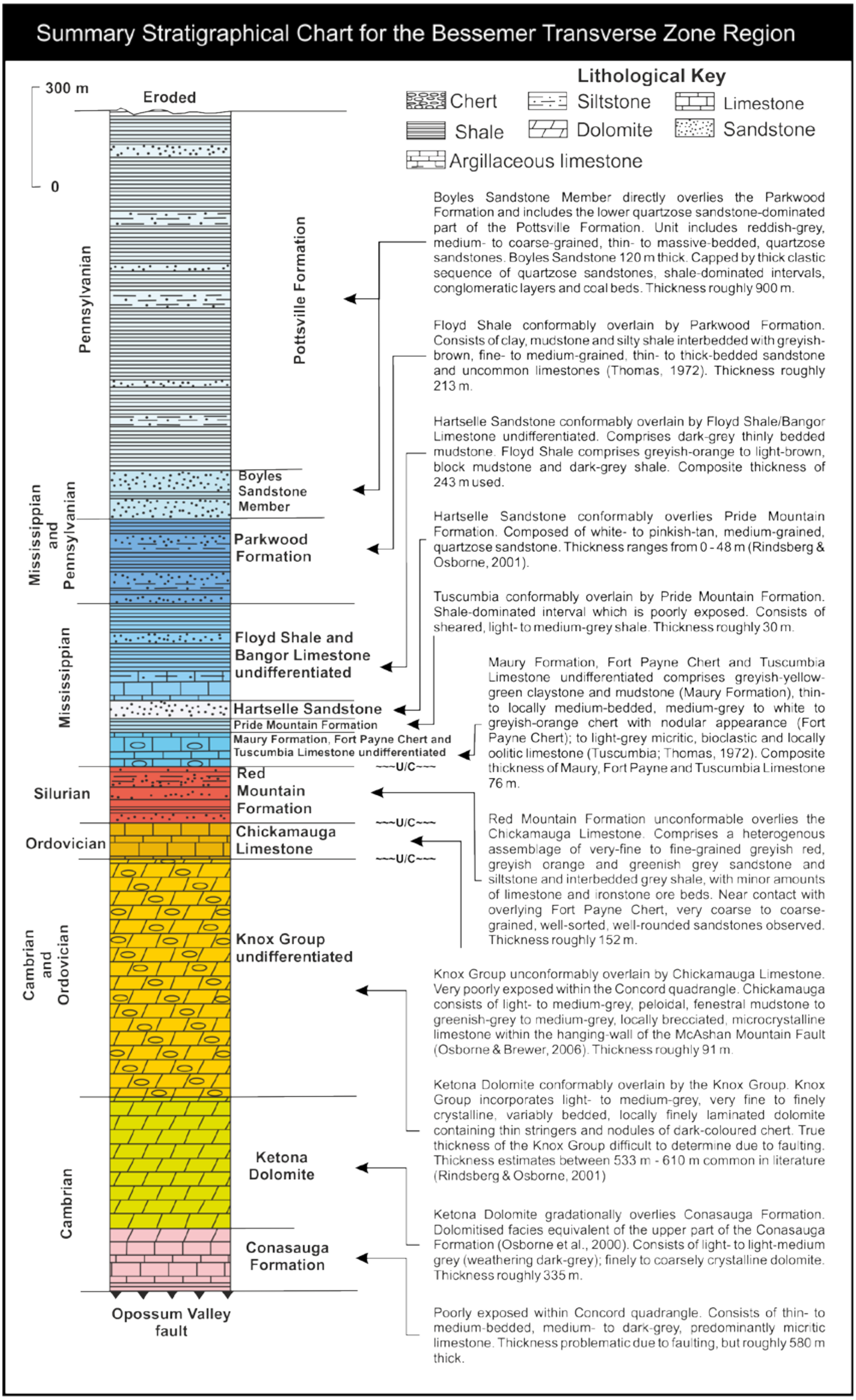


Figure 3.22: Generalised composite stratigraphical column of the Paleozoic rocks exposed within the Concord 7.5-minute quadrangle, Jefferson County, Alabama, southern Appalachians, USA. These units comprise those identified within the Bessemer Transverse Zone and 'The Knot' (Adapted after Irvin, 2008)

Numerous transverse zones have been mapped within the southern Appalachians of Georgia and Alabama including the Rome, Clinchport, Rising Fawn, Anniston, Harpersville, and Bessemer transverse zones (Brewer, 2004 and references therein). The Bessemer Transverse Zone marks the southernmost transverse zone exposed within the southern Appalachians, Alabama, and was chosen as the case example area for the development of the new methodology based on its well-constrained and documented development within Brewer (2004) (Figure 3.23).

During fault network analyses within the Bessemer Transverse Zone, a structure known as 'The Knot', has been identified as a key structure within a fault system laterally transferring displacements from the Blue Creek Fault and Opossum Valley Fault in the north to the Opossum Valley Fault and Jones Valley Fault in the south (Figure 3.23a; 3.23b). Cross-strike transfer is accommodated via several lateral thrusts which connect these dominant thrusts, including the Little Blue Creek Fault and the McAshan Mountain Fault (Figure 3.23a; 3.23b). This along-strike transfer has been classified as a displacement-transfer zone over a dextral lateral ramp (Brewer, 2004).

Within the regional-scale fault network analyses, long footwall ramp profiles are identified within the Jones Valley Fault (Figure 3.23b [1, 2, 3]) cutting up stratigraphical succession southwards. This structure is interpreted by Brewer (2004) as an out-of-sequence thrust developing after the forelandward Blue Creek and Opossum Valley faults. As such, deformation would be expected within the footwall of such a developing thrust, as highlighted by long frontal footwall ramp profiles (i.e., Figure 3.19c). Similar along-strike profiles are identified within the footwall of the Opossum Valley Fault near Bessemer (Figure 3.23b [4]), suggesting similar pulses of footwall deformation during alternating in-, and out-of-sequence thrust development. Conversely, within the regional Sole Thrust

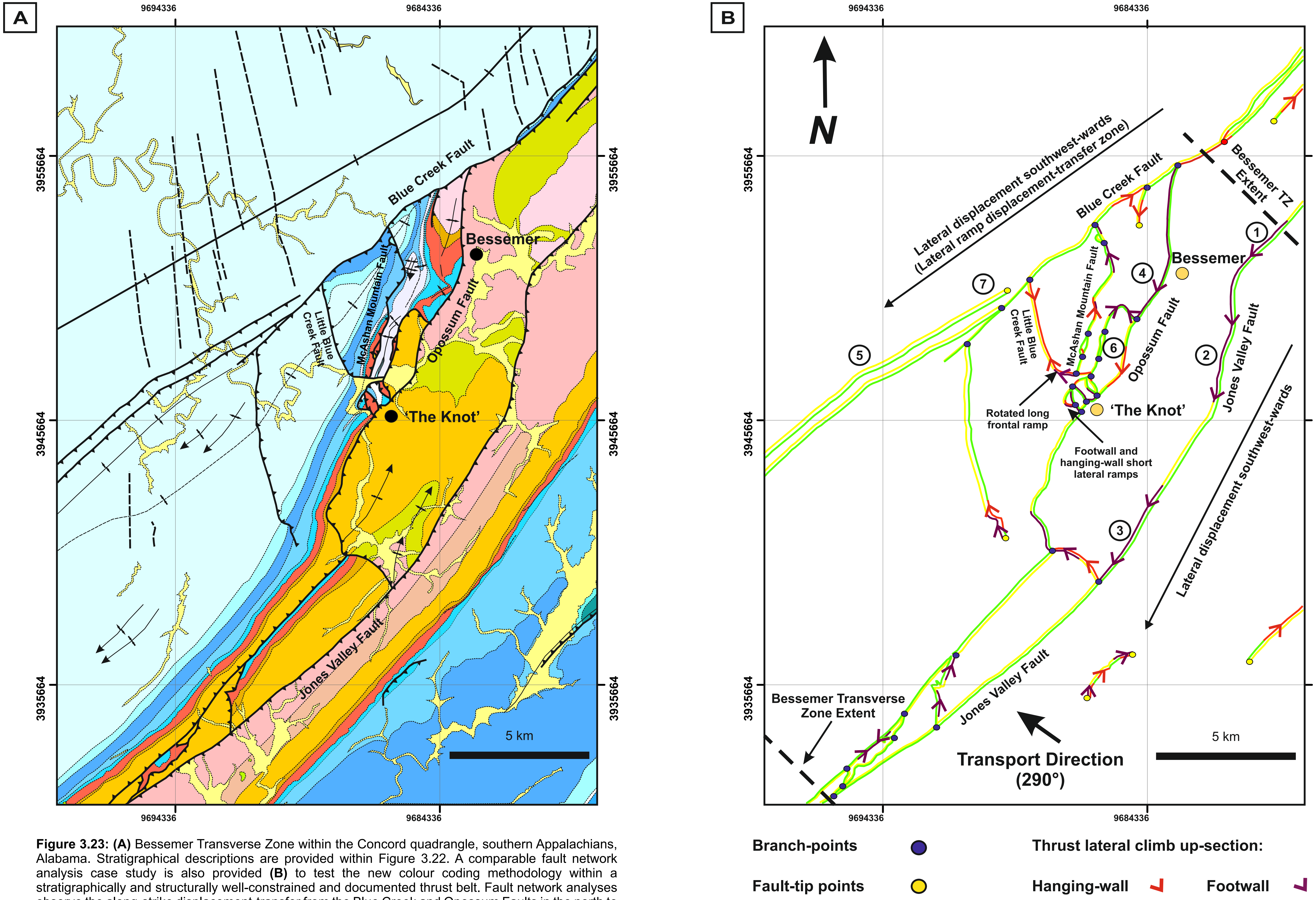


Figure 3.23: **(A)** Bessemer Transverse Zone within the Concord quadrangle, southern Appalachians, Alabama. Stratigraphical descriptions are provided within Figure 3.22. A comparable fault network analysis case study is also provided **(B)** to test the new colour coding methodology within a stratigraphically and structurally well-constrained and documented thrust belt. Fault network analyses observe the along-strike displacement-transfer from the Blue Creek and Opossum Faults in the north to the Opossum/Jones Fault to the south. This along-strike transfer has been interpreted as a lateral ramp displacement-transfer zone within Brewer (2004).

Zone (i.e., Blue Creek Thrust), a long profile displaying along-strike hanging-wall and footwall flats (Figure 3.19a; 3.23b [5]), with occasional hanging-wall ramps where anticline / syncline pairs interact within the Blue Creek Fault hanging-wall and the Opossum Valley Fault footwall are identified (Figure 3.23b [4]). Observations support Brewer's (2004) identifications suggesting that the Blue Creek and Opossum faults are kinematically linked during thrust development and translation.

Fault network architectural analyses of map-view spatial distributions of branch-points and fault-tip points further indicate a subsurface structure within this displacement-transfer structure. Branch-point clusters within the region of 'The Knot' indicate that displacement-transfer is focussed along-strike into this region as numerous thrust branches occur distributing displacement along-strike (Figure 3.23b [6]). Fault-tip analyses also terminate and / or nucleate sub-parallel to regional thrust transport direction (i.e., 290°; Brewer, 2004) within this region, further supporting a sub-surface cross-strike subsurface structure (Figure 3.23b [7]).

Within the immediate footwall of the Opossum Valley, 'The Knot' consists of four clustered horst blocks which are internally deformed (Figure 3.24). The north-eastern horst consists of Red Mountain Formation units within the footwall of the Knox Group undifferentiated horst block associated with the Opossum Valley Fault. The north-eastern horst block of Red Mountain Formation structurally overlies a central fault-bounded panel of Mississippian rocks ranging from Fort Payne Chert to Floyd Shale and Bangor Limestone undifferentiated. A second horst of Red Mountain Formation is southwest of the panel of Mississippian rocks. West of the south-western Red Mountain Formation block, another horst consists of a succession of Red Mountain Formation through Floyd Shale and Bangor Limestone undifferentiated (Figure 3.24). Orientation of structures within 'The

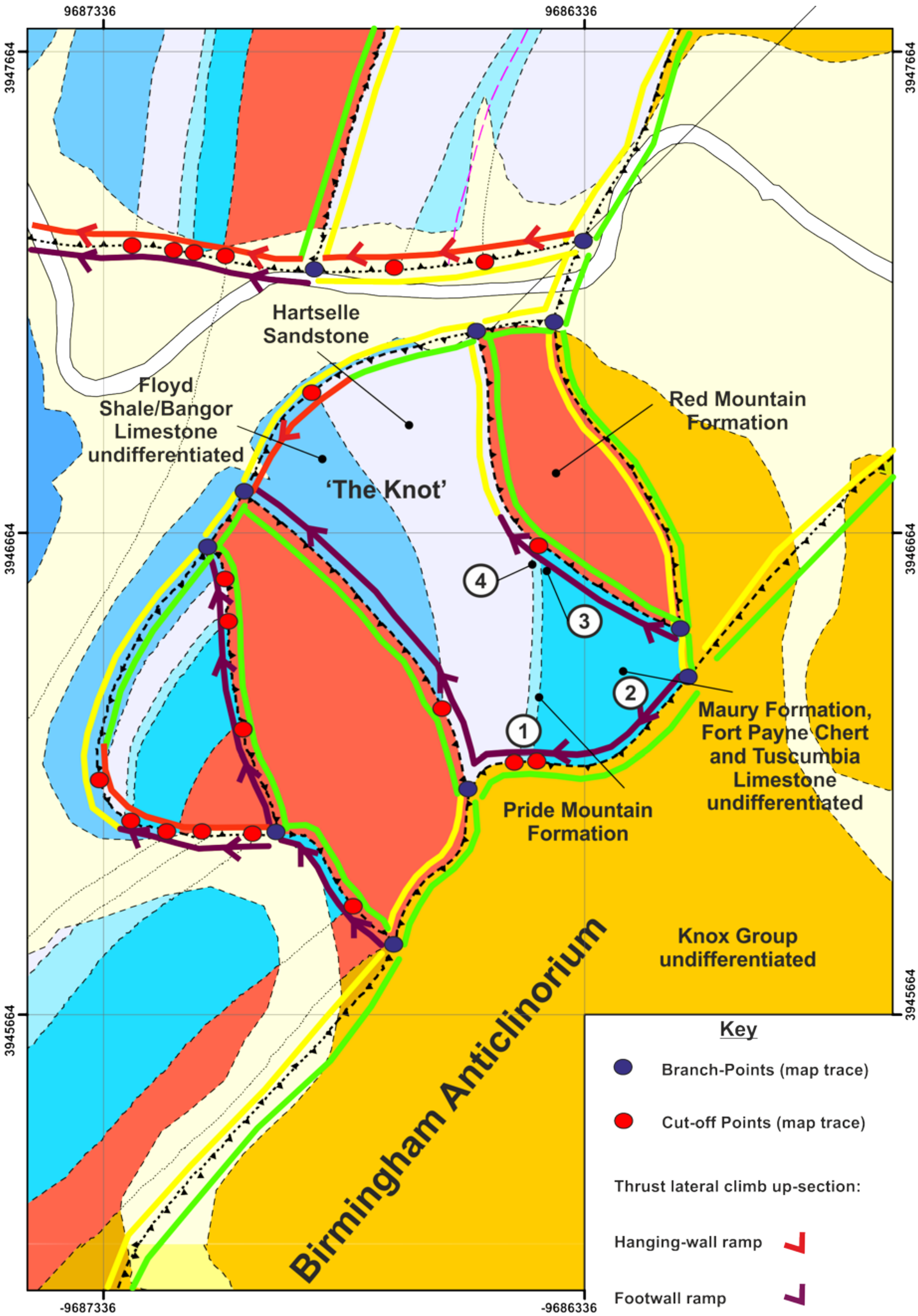


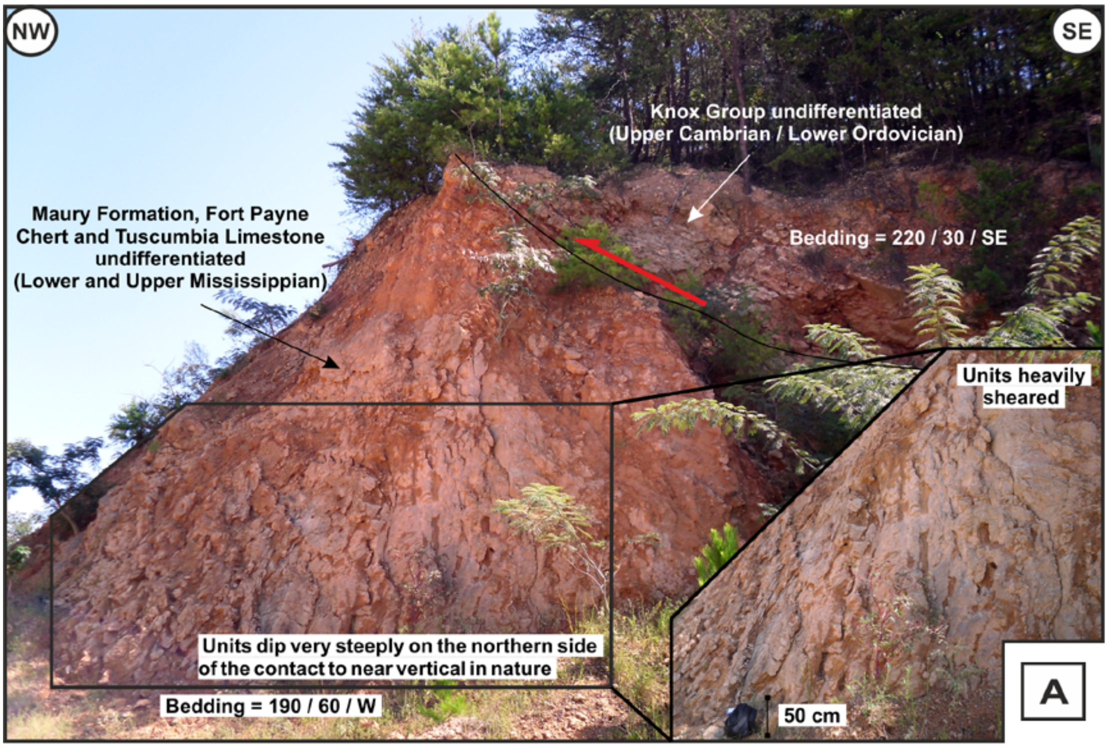
Figure 3.24: 'The Knot' within the Bessemer Transverse Zone. Distinct footwall ramps are identified within the four clustered horst blocks which compose 'The Knot'. These footwall ramp interpretations are verified within geometrical / kinematic data collections during fieldwork. Stratigraphical units are described within Figure 3.22. Locations of supporting geometrical and kinematic data are numbered.

Knot' with respect to structural strike in both the hanging-wall and footwall of the Opossum Valley Fault have been suggested by Brewer (2004) to identify that rocks in 'The Knot' were rotated independently during emplacement of the Opossum Valley Thrust Sheet. This observation by Brewer (2004) is supported within the fault network analysis by a series of footwall ramps all displaying lateral northwards climb within the core of 'The Knot' sequence (Figure 3.24). Fault network identifications are in turn supported by geometrical kinematic observations during fieldwork for this case study.

3.2.5.1. <u>"The Knot" fault network analysis: Geometrical and kinematic supporting data</u>

Since the work of Brewer (2004), when 'The Knot' was a small active quarry of the Bessemer Powder Plant (Thomas, 2011, pers. comm.), and the regional review of the Concord quadrangle of Jefferson County, Alabama (Irvin, 2008), exposure of 'The Knot' is limited by vegetation cover following quarry closure. However, contact between the north-easternmost horst block within the footwall of the Knox Group undifferentiated horst block, associated with the Opossum Valley Fault, containing Red Mountain Formation sandstones and the central fault-bounded panel of Mississippian rocks ranging from Fort Payne Chert to Hartselle Sandstone is still visible within the quarry walls allowing geometrical and kinematic observations.

Within the south-eastern corner of 'The Knot' contact of the Opossum Valley Fault and 'The Knot' is established indicating a top-to-northwest thrust translation (Figure 3.24 [1]; 3.25a). Knox Group undifferentiated units are viewed within the Opossum Valley Fault thrust hanging-wall dipping at 30°, compared to a laterally westward-rising footwall ramp composed of Maury Formation, Fort Payne Chert and Tuscumbia Limestone units dipping very sharply 60° to the west (Figure 3.25a). Further eastwards along-strike of the footwall ramp, a distinct kink is identified. Within this thrust kink zone, large fault



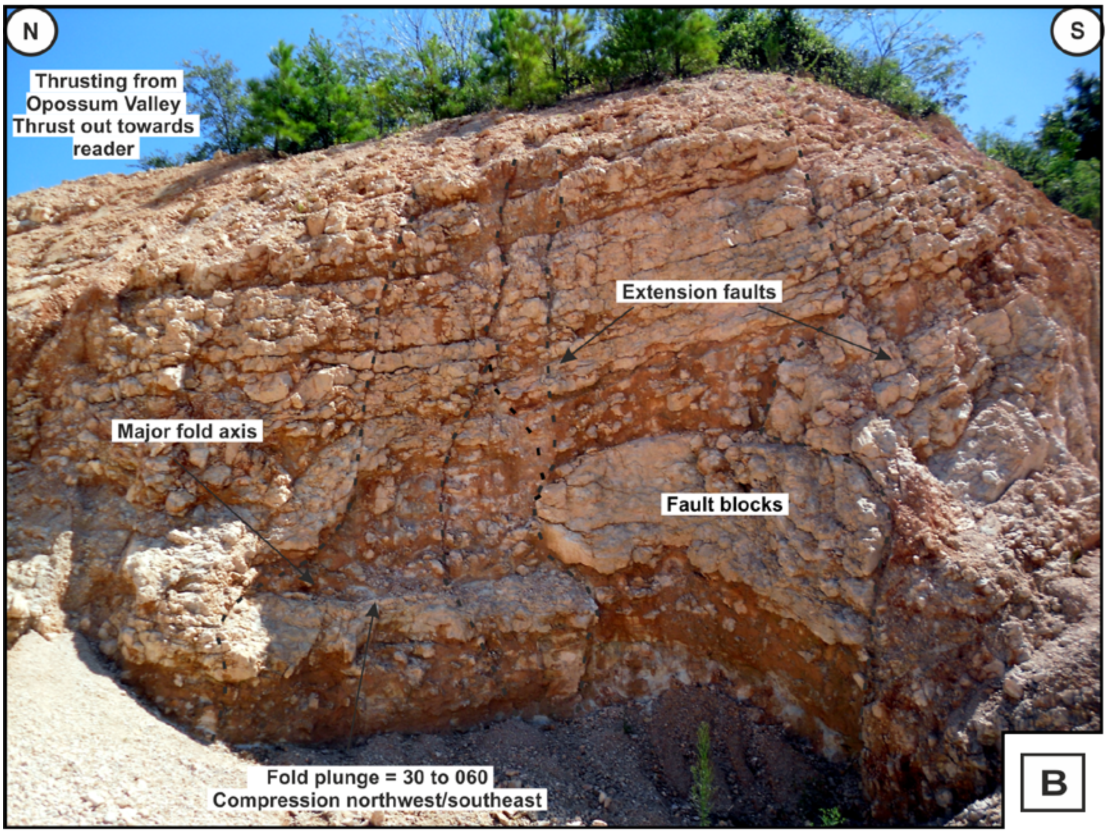


Figure 3.25: Geometrical observations supporting footwall ramp deformation within the south-eastern portion of 'The Knot' (highlighted within Figure 3.24). **(A)** Thrust contact between the Knox Group undifferentiated and underlying Maury Formation, Fort Payne Chert, and Tuscumbia Limestone undifferentiated indicating drastic along-strike variations in footwall stratigraphical dips. Footwall units are also heaving sheared along-strike (Insert). Thrusting top-to-northwest. **(B)** Further north-east along-strike within Opossum Valley Fault footwall, large footwall folds exposed indicate a northeast-southwest sense of compression not indicative of a top-to-northwest thrust translation typical of the Opossum Valley Thrust or southwest-translation within northern portions of 'The Knot'. Large fault blocks are also identified bounded by later extension or strike-slip faults cutting through these older footwall fold structures.

blocks and footwall folds plunging 30° to the west-southwest are identified within the Maury Formation, Fort Payne Chert and Tuscumbia Limestone undifferentiated units (Figure 3.24 [2]; 3.25b). These units show evidence of footwall deformation in response to thrust development further north within the central panel, where the north-eastern horst block containing Red Mountain Formation units are thrust south-westward. However, these distinct footwall folds suggest a northwest-southeast compressional regime, thereby supporting suggests of potential rotational thrusting within 'The Knot'. These folds are cut by later strike-slip or extension faults within the footwall strata.

Within the footwall of the north-easternmost horst block containing Red Mountain Formation units within its hanging-wall, extremely severe footwall deformation occurs within the underlying Mississippian units (Figure 3.24 [3]; 3.26a). Footwall bedding dips range from 40°to 60° within the north-western section of the quarry wall (Figure 3.26b) to locally overturned further towards the southeast (Figure 3.26c). Small footwall thrust splays indicate back-steepening south-eastwards as a result of potential rotational thrusting. These small thrust splays also indicate a localised thrust translation direction towards the west-northwest within this section (Figure 3.26). These observations are further supported by heavily deformed sandstone and shale units of the overlying Pride Mountain Formation (Figure 3.24 [4]; 3.27a). Units show detailed kinematic indicators (i.e., plunging folds), indicating a uniform plunging trend ranging between 20°to 25° dip towards 168°to 188° down-plunge (north / south; Figure 3.27b; 3.27c). A thrust translation direction of top-to-west within this section of the central panel is therefore apparent, similar to the west-north-westward translation twenty metres away. Folded units also illustrate earlier extension faults which when rotated back to pre-deformation positions suggest east-west dipping extension (Figure 3.27c).

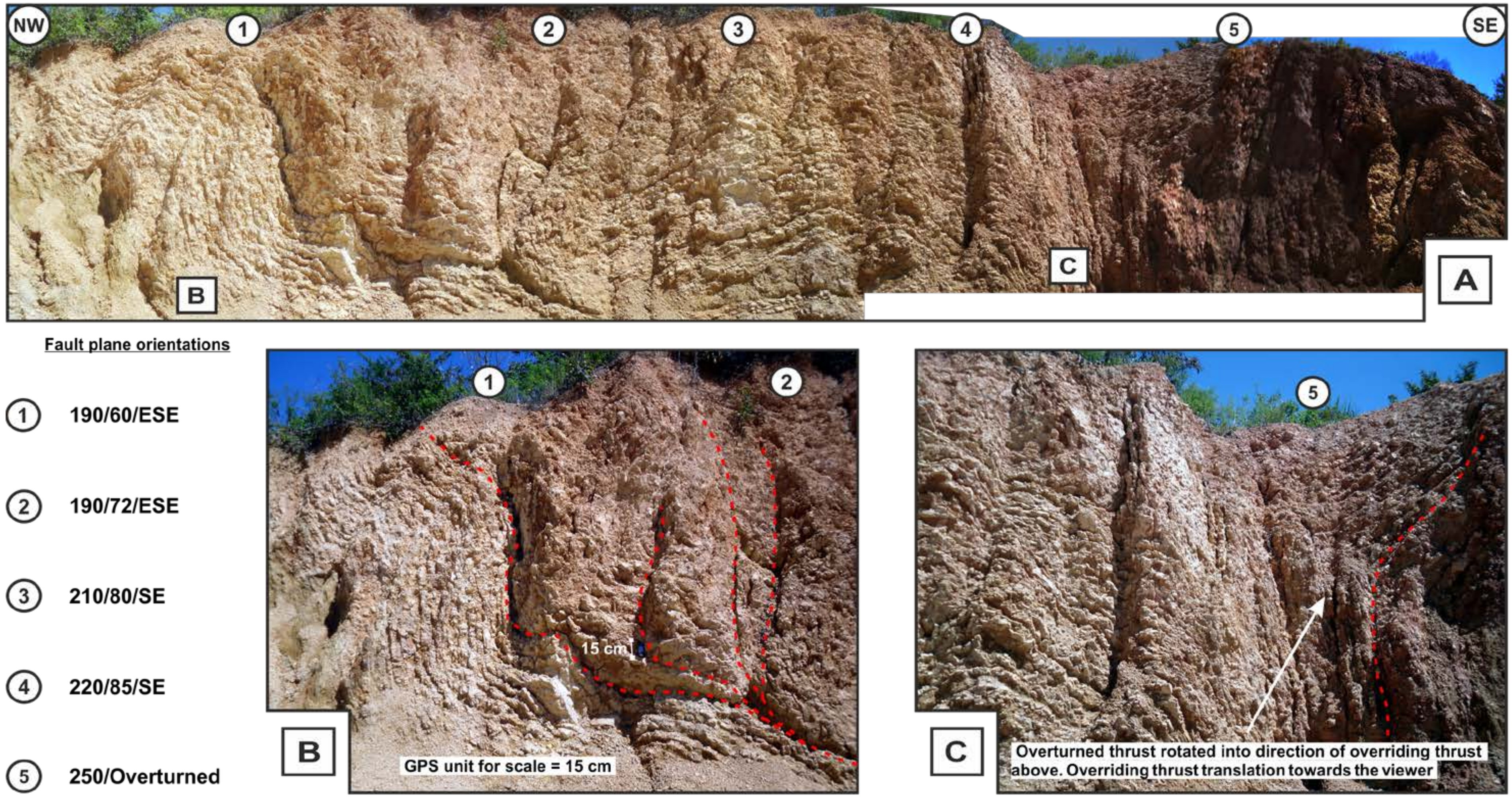


Figure 3.26: (A) Overview of deformation within the footwall of the north-easternmost horst block within 'The Knot'. Units comprise the Mississippian Maury Formation, Fort Payne Chert, and Tuscumbia Limestone undifferentiated. Drastic along-strike changes in dip are visable indicating numerous footwall thrust splays which have been back-steepened southeastwards. **(B)** Footwall thrust splays indicate thrust translation directions towards the west-northwest, compared to dominant south-west verging thrusts which override this footwall section indicating differential footwall stress fields along-strike. **(C)** Within the southeastern portions of the footwall sequence, thrust splays become locally overturned and rotated in regard to the overriding dominant thrust plane structurally above. Locations of structures depicted within Figure 3.24

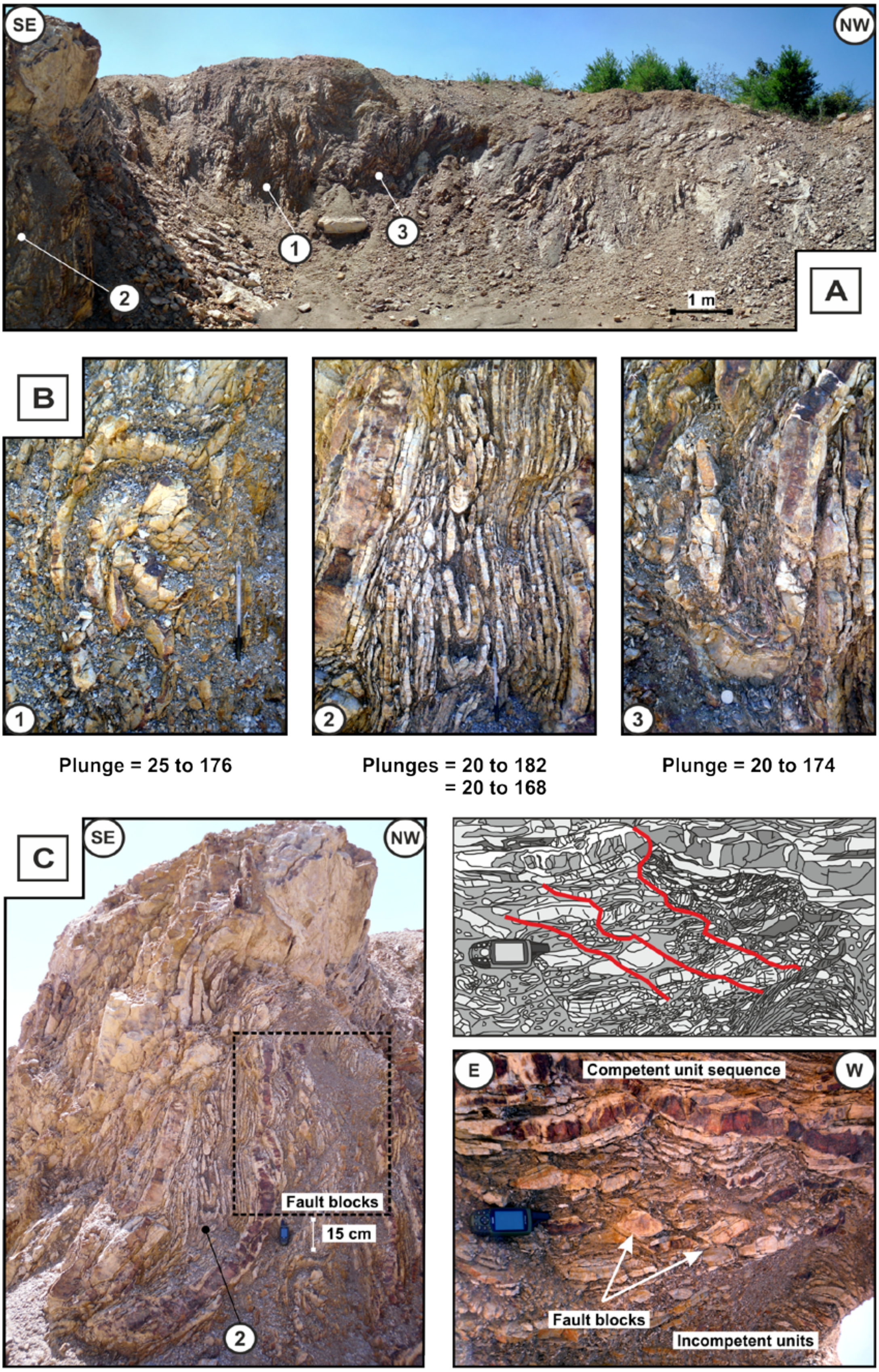


Figure 3.27: **(A)** Overview of the transition zone from Maury Formation, Fort Payne Chert and Tuscumbia Limestone to shale-dominant Pride Mountain Formation. Individual structural data locations are labelled. **(B)** Kinematic indicators (i.e., plunging folds) ranging from 20°-25° towards 168°-188°, indicating a east-west compression regime. Relative position within sequence is highlighted within (A) and (C). **(C)** Heavily folded units within a preserved stack depicting a top-to-west thrust translation. Earlier extension faults are also observed (highlighted in red), which when rotated into pre-deformation position suggest east-west dipping faults. GPS unit for scale = 15 cms.

Geometrical and kinematic evidence supports a series of footwall ramps, identified within the regional fault network analyses, which have undergone independent rotations during thrust emplacement from a top-to-southwest regime within hanging-wall units within the most north-eastern horst block, to a top-to-northwest regime within the footwall, supporting Brewer’s (2004) interpretations.

3.2.6. Implications: Review of new methodology / techniques

Prior to utilisation within the Moine and Cantabrian thrust belts, new methodologies were reviewed to identify what can be derived from these analyses and what advantages and / or disadvantages were observed which might need remediation and / or refinement.

3.2.6.1. New methodology: Advantages

Unlike certain previously utilised methodologies and techniques within cross-strike discontinuity and transverse zone research which may be costly and / or restricted within their utilisation, new fault network analyses developed within this research may be applied prior to fieldwork as a low-cost desk-based technique or during fieldwork to focus and test along-strike structural developments within fold-thrust belts. New methodologies add weight to previously utilised methodologies allowing identifications of thrust ramp-flat geometries along map-traces on a variety of spatial scales, whilst the implementation of a colour codex, when applied with geometrical and kinematic data, allows ramp classifications (i.e., frontal, lateral or oblique) to be determined within the hanging-wall and footwall respectively. Facing of lateral and oblique ramps are also determined, thus alleviating problems identified within Kwon & Mitra (2012) between lateral ramp and displacement-transfer identifications along-strike.

New fault network analyses allow along-strike structural changes to be categorised into fault- and / or fold-dominant zones, whilst map-view spatial distributions of branch-points, fault-tip points, cut-off points and thrust ramps allow along-strike identifications of potential cross-strike discontinues and sub-surface irregularities within the pre-thrust template to be observed, particularly where map-view features cluster or are alignment sub-parallel to regional transport. Furthermore, fault network analyses allow abrupt or gradual along-strike structural changes and phases of deformation to be identified (i.e., forelandward versus hinterlandward thrust propagation).

3.2.6.2. New methodology: Disadvantages and areas of remediation

Alternations between different spatial-scales within this new methodology do present various challenges which need to be remedied. Lateral ramps and transverse structures can potentially create structural sidewalls, along which different structural development may nucleate (i.e., cross-strike discontinuity phenomena). Along-strike topographical effects, which could in map-view be identified as cross-strike discontinuities or cross-strike discontinuity phenomena, have been removed during initial interpretation to allow the determination of primary structures (i.e., lateral ramps located over basement-related structures, rather than secondary re-orientations of lateral structures). Over regional-scales, topographical effects are nullified by scale of observation. However, focused detailed studies from regional-scale observations require greater attention. To accomplish this, detailed geometrical and kinematic data are required during fieldwork to verify (i.e., ground-truth) along-strike map-view interpretations.

3.3. Work-flow: Moine and Cantabrian thrust belts

This section describes the work-flow applied within the Moine and Cantabrian thrust belts for determining:

- the three-dimensional architecture of, and linkages across, transverse zones;
- the role of thrust translation (i.e., regional transport), in relation to potential pre-existing transverse structures;
- the effect / control that pre-thrust template architecture exerts upon transverse zone formation.

The following subsections describe the implementation of the new thrust ramp colour coding technique for identifying and geometrically analysing cross-strike discontinuities over regional scales within the Moine and Cantabrian thrust belts. Selected techniques applied in previous cross-strike discontinuity identifications are also incorporated allowing the identification and analysis of cross-strike discontinuities and transverse zones over varying spatial scales. A work-flow diagram (Figure 3.28) demonstrates the application of these different methodologies whereby the different scales of observation have been analysed and interpreted. Previously applied methods within transverse zone research that have been implemented within this work include:

- Geological map analyses,
- Ground-truth validations and / or detailed re-mapping,
- Collection of new geometrical and kinematic data,
- Photo-montages and geological overlays of complex thrust terrains,
- Transport-parallel and transport lateral cross-section construction,
- Stratigraphical separation diagrams.

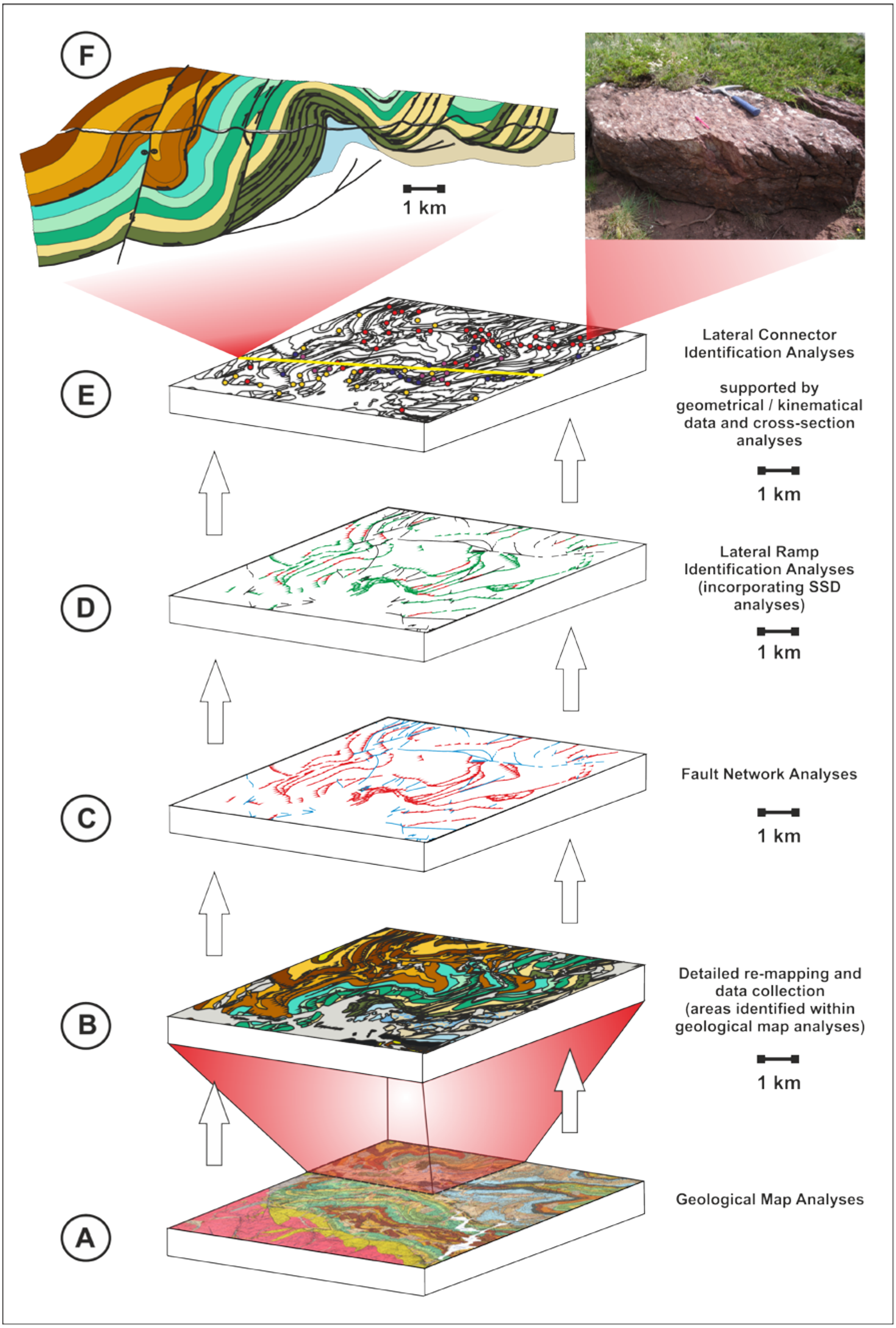


Figure 3.28: Work flow diagram highlighting the development of the new lateral ramp identification methodologies alongside 'tried and tested' methodologies. **(A)** Regional geological map analyses are primarily undertaken alongside **(B)** detailed re-mapping. **(C)** Fault network analyses are undertaken to determine chronology of deformation. **(D)** New methodologies for lateral ramp identifications are undertaken, while new lateral connector identification techniques are applied **(E)**. Methodologies are supported by cross-sectional analyses and geometrical / kinematical analyses of thrust map-traces **(F)**.

3.3.1. Geological map analyses

Previous research within transverse zone identification highlights the importance of observing cross-strike discontinuities / transverse zones on a variety of scales (e.g., Wheeler, 1980; Thomas, 1990). A combination of regional and localised outcrop characteristics including, large-scale geometrical style changes and cross-strike linkages, characterise transverse zone evolution (Thomas, 1990). Therefore, analyses of regional and localised outcrop expressions of cross-strike discontinuities, using desk-based analyses of geological maps on a variety of scales were undertaken (Figure 3.28a).

Two tiers of observation were implemented within the Moine and Cantabrian thrust belts:

- <u>Regional (1:625,000 to 1:50,000-scale) map resolutions</u> were used to identify the areal extent of the transverse zones as a whole within the fold-and-thrust belt, including large-scale structural style analyses of all major thrust faults and thrust-related folds transecting potential transverse zones within the Moine thrust belt (e.g., British Geological Survey, 1913; 2008) and the Cantabrian thrust belt (e.g., Alonso, 1989; Alonso *et al*., 1989; Álvarez-Marrón *et al*., 1989; Bastida & Gutiérrez, 1989; Jorge Marquinez, 1989). Furthermore, lateral facies, stratigraphical thickness changes and structures were identified. Lateral structures were classified as pre-, syn-, or post-depositional in age where possible.

- <u>Local (1:25,000 to 1:10,000-scale) map resolutions</u> analyses were used to identify finer scale transverse zone structures, such as cross-strike links (e.g., Johnson, 1958; 1960; Matthews, 1984). These where supplemented by detailed (1:10,000-scale) re-mapping of key structures within the current research.

3.3.2. Ground-truth validations and / or detailed re-mapping

Changes in bedding and fault orientations, stratigraphical décollement levels, and structural style of major faults are typical features of transverse zones in map-view (e.g., Thomas, 1985, 1990; Brewer, 2004; Cook, 2010). Detailed ground-truthing and / or remapping were carried out in areas of abrupt along-strike variations / terminations of thrusts and folds identified within the initial geological map analyses (Figure 3.28b).

Key structural measurements including along-strike variations in strike and dip of bedding orientations, fold and thrust map trends, and fold plunge orientations from previous and new structural datasets were recorded on the geological maps to determine along-strike variations in structural style. Fault surfaces were taken from the original survey line-work within the desk-based geological map analyses and remapped where appropriate with modern field-study based observations and interpretations.

New transverse zone maps incorporating areas of 1:10,000-scale remapping were completed within the

- north-western sections of the Achnashellach Culmination within the Kinlochewe region along the northern and southern walls of the Loch Maree Fault from Beinn Eighe to the Heights of Kinlochewe;
- San Emiliano region of the south-western hinge of the Cantabrian Thrust Belt between the Huergas de Babia Valley and the Genestosa Fault system.

Details of the relationships between cross-strike links and major thrust sheets were established using these smaller-scale maps and the construction of transport-lateral and transport-parallel cross-sections.

3.3.3. Geometrical and kinematic data collection and analysis

Whether a particular part of a specific cross-strike discontinuity overlies, or once interacted with, underlying basement faults or regional transport transverse structures, is a question answerable only with local data (e.g. Wheeler, 1980; Thomas, 1990). Therefore, detailed geometrical and kinematic data were collected and analysed over a variety of scales as part of the 1:10,000-scale remapping process (Figure 3.28b; 3.28f). Geometrical data were collected to determine the evolution of along-strike variations in structural geometry, to establish potential cross-strike linkages and to determine chronologies of deformation through cross-cutting relations.

Detailed geological mapping identified dominant ramps within the thrust sequences, reactivations of pre-existing structures through processes such as inversion, and out-of-sequence thrusting indicating alternations between foreland- and hinterland-propagating thrust systems. Localised buttressing effects (i.e., formation of duplex structures and antiformal stacks) were observed along-strike indicating potential interactions of frontal and transport-parallel lateral structures.

Photo-montages of large-scale geometrical expressions of along-strike variations in structural and stratigraphical styles were used to highlight the geometrical and kinematic cross-strike linkages within the study areas. Outcrop-scale photographic data collection of structural to stratigraphical relationships were also undertaken to identify cross-cutting relationships within the thrust systems and determine thrust propagation sequences. Photographic data collections of geometrical styles range from fault-propagation folds and hanging-wall anticlines to varying along-strike imbrication styles. Collections of geometrical data on these various scales are assisted by transport-lateral and transport-parallel cross-sections.

Kinematic indicators comprising asymmetrical deformation structures can be used to determine the sense of shear linked to their formation and exist on various scales (Cosgrove, 2007). Kinematic indicators used within the context of this work range from outcrop-scale observations to large-scale regional expressions including:

- penetrative asymmetric cleavages,
- deformed veins along thrust planes
- slickensides indicating shear elements of movement along fault and bedding planes,
- deformed trace fossil burrows (i.e., *Skolithos* and *Monocraterion* burrows)
- fault-propagation folds, sheath folds, and hanging-wall anticlines.

Detailed analyses of these kinematic indicators allowed the determination of regional transport direction within the thrust system thereby allowing the alignment of transport-lateral and transport-parallel cross-sections. Furthermore, regional- and / or localised-scale variations to regional transport are observed indicating along-strike deflections of stratigraphy relative to the regional transport direction.

3.3.4. Fault network analyses: Thrust ramp colour coding and stratigraphical separation diagrams

Regional analyses of the interplay of different structural components within the thrust systems (i.e., the fault network, Figure 3.28c-e) were analysed to identify:

- along-strike changes in structural and stratigraphical styles (i.e., folding versus faulting-dominant domains)

- along-strike relationships between thrust ramp styles and their respective orientations to regional transport (i.e., thrust facing),
- along-strike spatial analyses of thrust linkages and their orientations within the fault systems (i.e., branch-lines, fault-tip points and cut-off points).

Within the Moine and Cantabrian thrust belts, these methodologies were applied in different ways and on differing spatial scales. Within the Kinlochewe region of the Moine thrust belt, regional-scale fault network analyses (Figure 3.28c) were superseded by 1:10,000-scale mapping as only a comparatively small area was under investigation. Within the Cantabrian Thrust Belt, fault network analyses were applied over the whole thrust belt to identify along-strike variations in structural and stratigraphical styles (i.e., identification of potential transverse zones) prior to detailed field analyses.

Thrust colour coding analyses and thrust facing analyses (Figure 3.28d) were implemented in both study areas to determine thrust ramp orientations (i.e., frontal, lateral or oblique ramp identifications) and thrust facing characteristics (i.e., ramps cutting up or down stratigraphical section). These analyses were used for the identification of cross-strike linkages developed within the allochthonous cover strata as a result of pre-thrust template irregularities. Along-strike thrust ramp characteristics were constrained by observations within the new 1:10,000-scale remapping, geometrical and kinematic data acquisition and cross-section constructions. Furthermore, cross-strike linkages were identified within the Moine and Cantabrian thrust belts through along-strike distributions of fault branch-lines, fault-tip lines and cut-off point analyses (Figure 3.28e).

Construction and analyses of transport-perpendicular stratigraphical separation diagrams have been used compiling data identified within preliminary geological map analyses and detailed remapping. Stratigraphical separation diagrams are applied within the study areas as a desk-based application to identify along-strike lateral variations in thrust décollements, compartmentalisations of the thrust belt by transverse faults, and potential lateral ramp identifications through ramp-flat geometrical observations. Furthermore, stratigraphical separation diagrams are utilised to test previous interpretations within the Kinlochewe region of the Achnashellach Culmination (e.g., Butler *et al*., 2007).

3.3.5. Cross-section construction

Detailed 1:10,000-scale remapping allowed the generation of transport-parallel and transport-lateral geological cross-sections from the new transverse zone map compilations constrained by geometrical and kinematic data. Transport-parallel (strike-perpendicular) cross-sections have been constructed to identify cross-strike linkages, including dominant frontal features, such as, frontal ramps. Frontal ramps frequently terminate abruptly along-strike at transverse zones creating structural compartmentalisations within the thrust transport (e.g., duplexes and antiformal stacks). Frontal ramps commonly have links with inherited features within the pre-thrust template including, normal and / or sub-décollement basement faults which have been reactivated during the kinematic development of the transverse zone. Buttressing effects along pre-existing structures within the pre-thrust template (e.g., transverse structures and / or structural highs) have constrained or aligned transverse zones within the study areas.

Whilst many authors have produced transport-parallel (strike-perpendicular) cross-sections within the Moine and Cantabrian thrust belts, few studies have constructed transport-lateral (strike-parallel) cross-sections within the Moine or Cantabrian thrust belts to identify cross-strike discontinuities. Transport-lateral (strike-parallel) cross-sections were constructed to determine lateral changes in thrust décollements, cross-strike linkages and potential pre-thrust lateral variations. Construction of transport-parallel and transport-perpendicular cross-sections allows the production of 'fence diagrams' whereby the pseudo-three-dimensional properties of cross-strike linkages are viewed (e.g., Snedden & Sprang, 1989, 1990; Wilkerson *et al*., 1991).

3.4. Summary

During review of pertinent cross-strike discontinuity and transverse zone identification techniques and methodologies, numerous viable techniques are identified. However, not all techniques are able to be utilised within a given geological setting, either as a result of local geological complexities, data restrictions, or are not economic viable. Furthermore, a distinct paucity in research concerning map-view spatial distribution analyses of thrust ramps and thrust architectural component alignments within cross-strike discontinuity research was observed over various scales. Therefore a new methodology was developed within this research to bridge this divide.

Chapter three describes cross-strike discontinuity (CSD) methodologies developed to identify transverse zones on regional and localised outcrop expressional scales. Fault network analyses incorporate regional structural styles and thrust ramp colour coding methodologies. Branch-line, fault-tip line and cut-off point analyses determine thrust nucleation, propagation, termination and stratigraphical décollement relationships. Analytical methods described here add to the selected 'tried and tested' methods such as geological map interpretation, ground-truth validations and / or detailed remapping, and geometrical / kinematic data collection. Cross-section analyses, stratigraphical separation analyses and graphical techniques, including photo-montages and geological overall production in complex terranes were also undertaken to determine:

- Three-dimensional architecture of, and linkages across, cross-strike discontinuities / transverse zones
- The role of thrust translation (i.e., regional transport), in relation to potential pre-existing transverse structures;
- The effect / control that the pre-thrust template exerts upon transverse zone formation

A work diagram demonstrates the application of different methodologies whereby the different scales of observations have been analysed and interpreted within the Moine and Cantabrian thrust belts.

Chapter Four:

Identification and analysis of Transverse Zones in Thrust Belts: Kinematic Partition across the Loch Maree Transverse Zone (southern wall), Moine Thrust Belt, Scotland

Chapter four serves to illustrate the findings undertaken as part of the remapping of the Kinlochewe region along the Loch Maree Fault southern wall within the Moine Thrust Belt, NW Highlands, Scotland. Emphasis is placed on the validation of new methodologies applied to identify transverse structures and cross-strike linkages within transverse zones. Results serve to define the kinematic evolution of the Loch Maree Transverse Zone (LMTZ), to differentiate lateral discontinuities that arise syn-kinematically during thrusting and pre-thrust discontinuities, and to provide insight into processes by which thrust-belt transverse zones may originate and evolve.

4.1. Introduction

New detailed 1:10,000-scale re-mapping (2009 to 2012) of the northern section of the Achnashellach Culmination is captured in a new geological map for the Kinlochewe region (Figure 4.1), and an array of cross-sections that examine the Loch Maree Transverse Zone (LMTZ). This new LMTZ map is confined between Beinn Eighe (southern wall of the LMTZ) and the Heights of Kinlochewe (LMTZ northern wall) and is transected by the Loch Maree Fault (LMF). Major thrusts such as the Moine Thrust and Kinlochewe Thrust were abstracted from previously constructed geological maps and verified (Figure 4.1).

New findings undertaken within this research build upon previous studies within this region (i.e., Peach *et al.,* 1907; Matthews, 1984; Butler *et al.,* 2007) and apply new

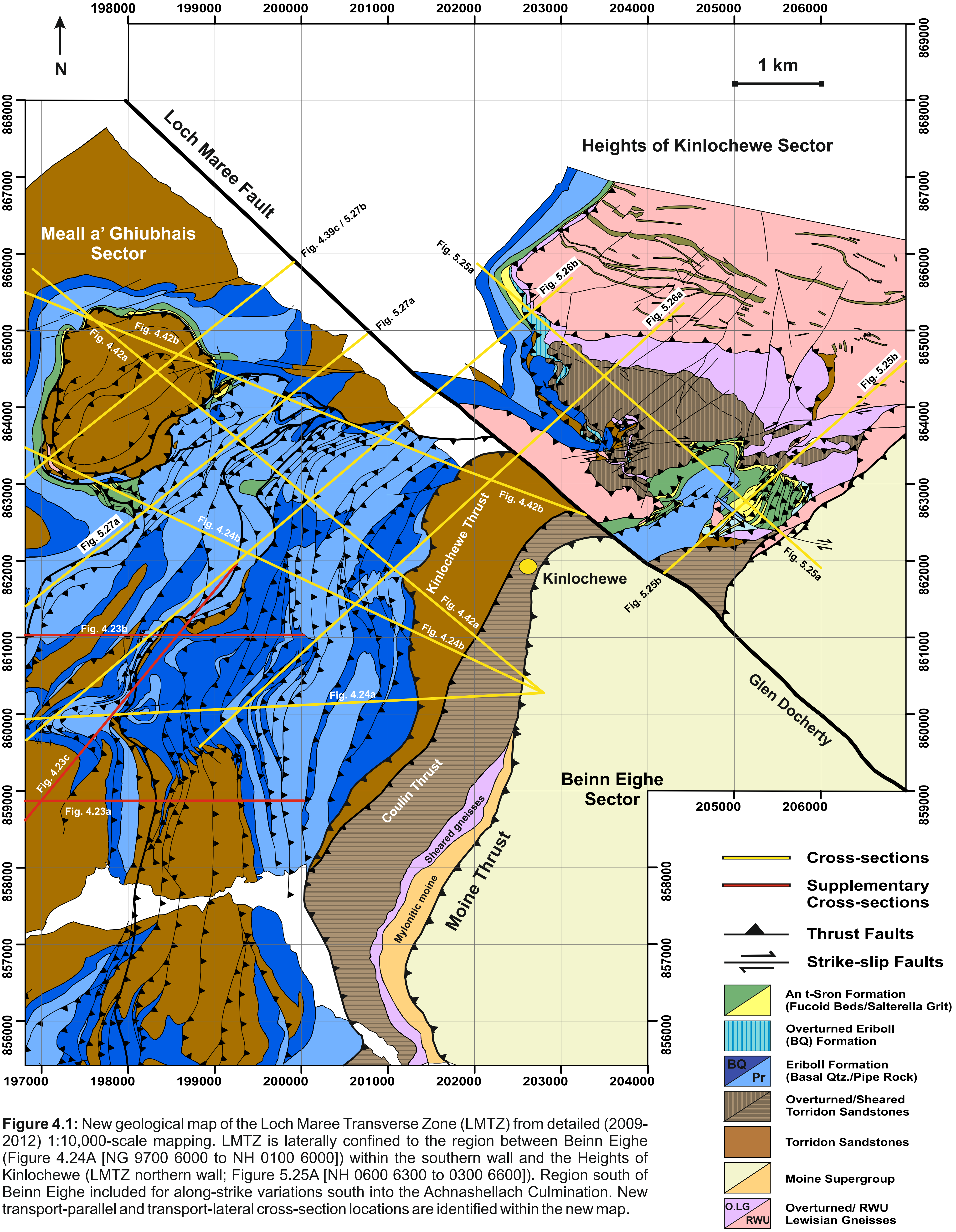


Figure 4.1: New geological map of the Loch Maree Transverse Zone (LMTZ) from detailed (2009-2012) 1:10,000-scale mapping. LMTZ is laterally confined to the region between Beinn Eighe (Figure 4.24A [NG 9700 6000 to NH 0100 6000]) within the southern wall and the Heights of Kinlochewe (LMTZ northern wall; Figure 5.25A [NH 0600 6300 to 0300 6600]). Region south of Beinn Eighe included for along-strike variations south into the Achnashellach Culmination. New transport-parallel and transport-lateral cross-section locations are identified within the new map.

interpretations, including the identification of several new thrust sheets (i.e., Coulin, Coire Each, Meallan Ghobhar and Heights of Kinlochewe). New findings permit a significantly different interpretation for the northern section of the Achnashellach Culmination and its evolution within the Moine Thrust Belt.

This chapter describes the geological setting (i.e., the Moine Thrust Belt) and reviews pertinent research within the Achnashellach Culmination. Detailed analyses of the Achnashellach Culmination fault network within this research are described and subsequently validated through detailed geometrical and kinematic observations during re-mapping within the southern and northern walls of the Loch Maree Transverse Zone (LMTZ). Observations are separated into distinct sectors and presented from hinterland to foreland within the transport direction and from south to north beginning with the Beinn Eighe sequence and culminating with the Heights of Kinlochewe sequence on the northern wall of the Loch Maree Fault (LMF). Observations within the northern wall of the Loch Maree Transverse Zone are discussed within chapter five. Cross-strike linkages are then identified and discussed to determine the role of the pre-thrust template on the development of the Loch Maree Transverse Zone.

4.2. Geological setting

The Moine Thrust Belt (Figure 4.2) is among the best exposed and studied fold-and-thrust belts in the world, and dominates the geological structure of the Northwest Highlands of Scotland, stretching for an on-land length of two hundred kilometres between Loch Eriboll and Skye south-westwards to the Sound of Iona, southwest Mull, totalling a distance of five hundred kilometres (Prigmore & Rushton, 1999; Strachan *et al.,* 2002). The belt developed during the Scandian (Silurian) phase of the Caledonian Orogeny (c. 435-415 Ma), as a result of Iapetus Ocean closure and the oblique convergence of three crustal

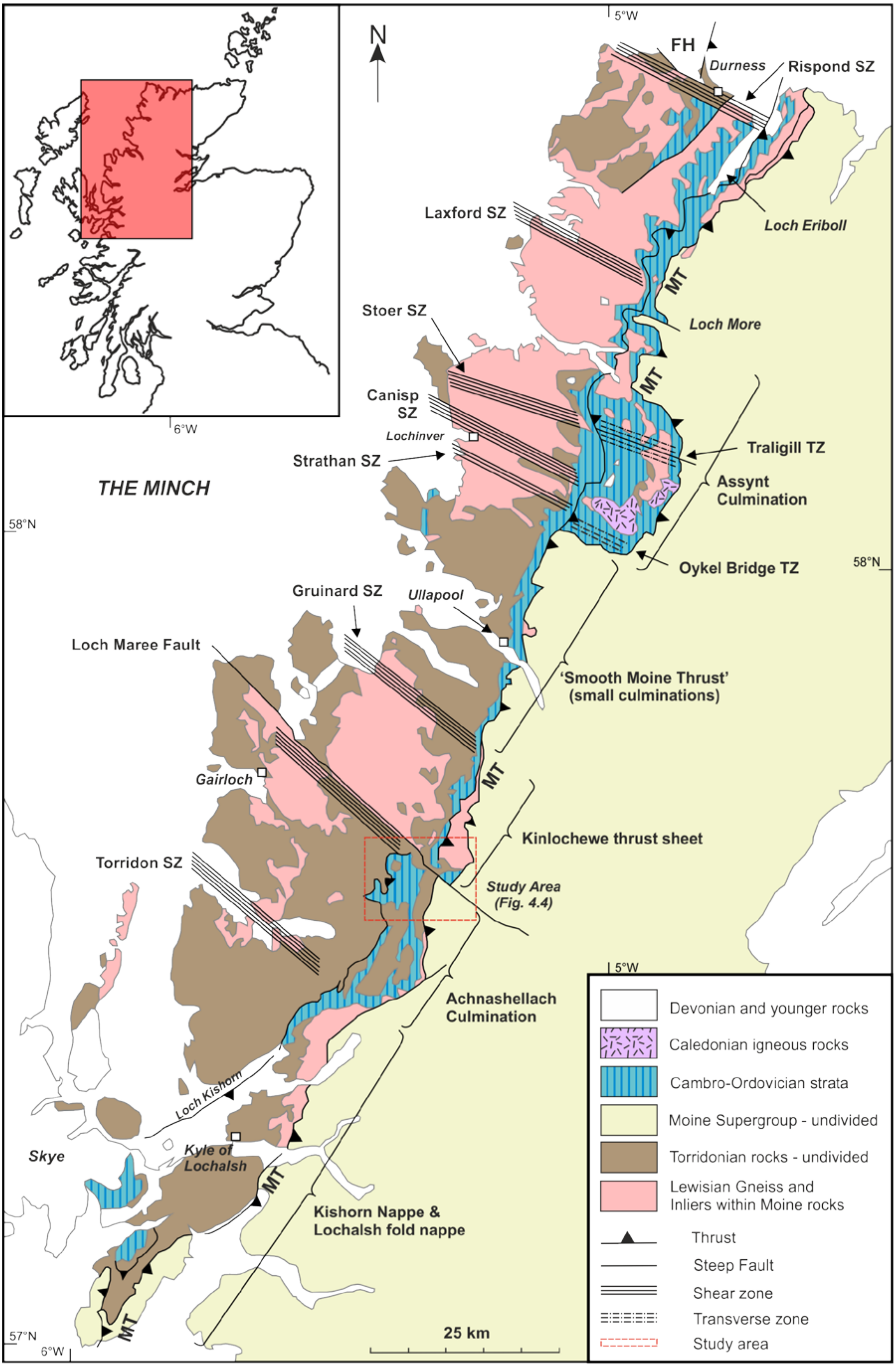


Figure 4.2: Geological map of the Moine Thrust Belt, NW Highlands. Proterozoic shear zones and related transverse zones are illustrated. MT, Moine Thrust. No details east of the Moine Thrust shown. Inset shows position of the study area within the northern Achnashellach Culmination (Figure 4.4) (Adapted after Krabbendam & Leslie, 2010).

blocks: Laurentia, Baltica and Avalonia (e.g., van Breeman *et al.,* 1979; Soper *et al.,* 1992; Freeman *et al.,* 1998; Dallmeyer *et al.,* 2001; Strachan *et al.,* 2002; Kinny *et al.,* 2003; Alsop *et al.,* 2010; Goodenough *et al.,* 2011 and references therein).

The roof of the Moine Thrust Belt is defined by the Moine Thrust (*sensu stricto*), a structure which carries the Neoproterozoic Moine Supergroup in its hanging-wall and represents the westernmost and youngest of the Scandian thrusts on the mainland of northern Scotland (Strachan *et al.,* 2002). This simple definition of the Moine Thrust does, however, present complications as this structure has been identified by various authors to have different ages of movement along-strike within various parts of the thrust belt (e.g., Strachan *et al.,* 2002; Butler, 2010; Goodenough *et al.,* 2011). U-Pb geochronology and Rb-Sr/K-Ar analyses indicate along-strike Scandian thrusting between c.435-429 Ma (Goodenough *et al.,* 2011). Several authors (e.g., Freeman *et al.,* 1998; Dallmeyer *et al.,* 2001) have suggested continued localised thrusting into the Early Devonian within the northern Moine Thrust Belt (c. 415-408 Ma). However, these younger dates have been suggested to relate to later brittle reactivations along the Moine Thrust (Goodenough *et al.,* 2011 and references therein). Within the Moine Thrust footwall, the Moine Thrust Belt consists of a series of thrust sheets transporting rocks which can be confidently correlated within the foreland.

Detailed analyses of the Moine Thrust and its footwall thrusts (i.e., Moine Thrust Zone), identifies a crustal-scale west-northwest-vergent (290 / 300°N) regional transport direction. Thrusts dip gently (<20°) to the east-southeast with estimates of eleven to seventy seven kilometres displacement along individual segments of the Moine Thrust combining to a minimum total of at least one hundred kilometres (e.g., Elliott & Johnson, 1980; McClay & Coward, 1981; Butler & Coward, 1984). Thrust vergence has been identified using several parameters including:

- Orientations of deformed pebbles within sheared Torridonian and Cambrian rocks;
- Stretching lineations within the mylonite belt;
- sense of shear shown by distorted *Skolithos* and *Monocraterion* burrows within the Lower Cambrian Eriboll Formation (Pipe Rock Member);
- Trends of thrusts and lateral ramps (Wilkinson *et al.,* 1975; McClay & Coward, 1981; Fischer & Coward, 1982; Butler & Coward, 1984; Strachan *et al.,* 2002; Park, 2002; Krabbendam & Leslie, 2004; 2010; Mendum *et al.,* 2009; Alsop *et al.,* 2010; Butler, 2010).

A general consensus within the Moine Thrust Belt is that thrusts propagated in a 'piggy-back' sequence towards the foreland (i.e. foreland-propagating, Elliott & Johnson, 1980; Coward, 1985). Overall forelandward-vergence is indicated by structurally higher thrusts being folded by duplex developments within their footwalls. However, along-strike out-of-sequence geometries (i.e., hinterlandward propagating) are not uncommon either as a result of late movement (e.g., Coward, 1982; 1983; 1985; Holdsworth *et al.,* 2006) or simultaneous slip on an array of imbricate thrusts (e.g., Butler, 2004).

Along-strike, the Moine Thrust Belt is in places a simple structure comprising a single thrust plane, with Moine rocks resting directly on the Foreland (i.e., 'Smooth Moine Thrust; Figure 4.2). Elsewhere these Moine rocks are dissected and repeated by a number of ductile thrusts arranged within a regional-scale structure that, like the Moine Thrust Zone structurally below, incorporates culminations and abrupt lateral variations such as the Assynt, and Achnashellach Culminations (Figure 4.2; Elliott & Johnson, 1980; Barr *et al.,* 1986; Butler *et al.,* 2007; Krabbendam & Leslie, 2004; 2010; Leslie *et al.,* 2010). Thrust sheets vary along-strike in thickness from kilometre-scale to less than ten metres, with a wide variety of thrust geometries present including; foreland and hinterland dipping-duplexes, anticlinal stacks, thrust nappes, true fold-nappes and lateral ramps (Krabbendam & Leslie, 2010).

A variety of crustal-scale segments demonstrating abrupt lateral variations have been observed within the Moine Thrust Belt including, the Oykel Bridge and Traligill transverse zones (Krabbendam & Leslie, 2010; Leslie *et al.,* 2010). These structures have been associated with the development of cross-strike discontinuities as a result of a step in basement related to west-northwest-east-northeast striking Palaeoproterozoic shear zones (i.e., Canisp, Stoer and Strathan shear zones, Figure 4.2; Attfield, 1987; Beacom *et al.,* 2001; Kinny *et al.,* 2005; British Geological Survey, 2007; Leslie *et al.,* 2010). A similar Palaeoproterozoic (Laxfordian) shear zone has been identified beneath the Loch Maree Fault within the Kinlochewe region, northern Achnashellach Culmination (e.g., Park *et al.,* 2001; Park, 2002; Butler *et al.,* 2007).

4.2.1. Pertinent lithologies within the Moine Thrust Belt: Achnashellach Culmination

West of the Moine Thrust Belt, within the undeformed foreland, oldest rocks comprise the Lewisian Gneiss Complex (i.e., foreland basement). Units are composed of felsic to intermediate Archaean orthogneisses (Scourian Gneiss), intruded by the subvertical Early Palaeoproterozoic mafic and ultramafic Scourie Dyke Swarm (Park *et al.,* 2002; Figure 4.3). A major unconformity separates the complex from the overlying early-Neoproterozoic Torridon Group comprising several kilometres of coarse red arkosic, often trough or planar cross-bedded sandstone. Soft sediment deformation structures are common (i.e., Applecross Formation). Heterolithic units of conglomerate, breccia, tabular sandstones and mudstone of the Diabaig Formation are locally present beneath the Applecross Formation (Figure 4.3; Van de Kemp & Leake, 1997; Stewart, 2002; Kinnaird *et al.,* 2007;

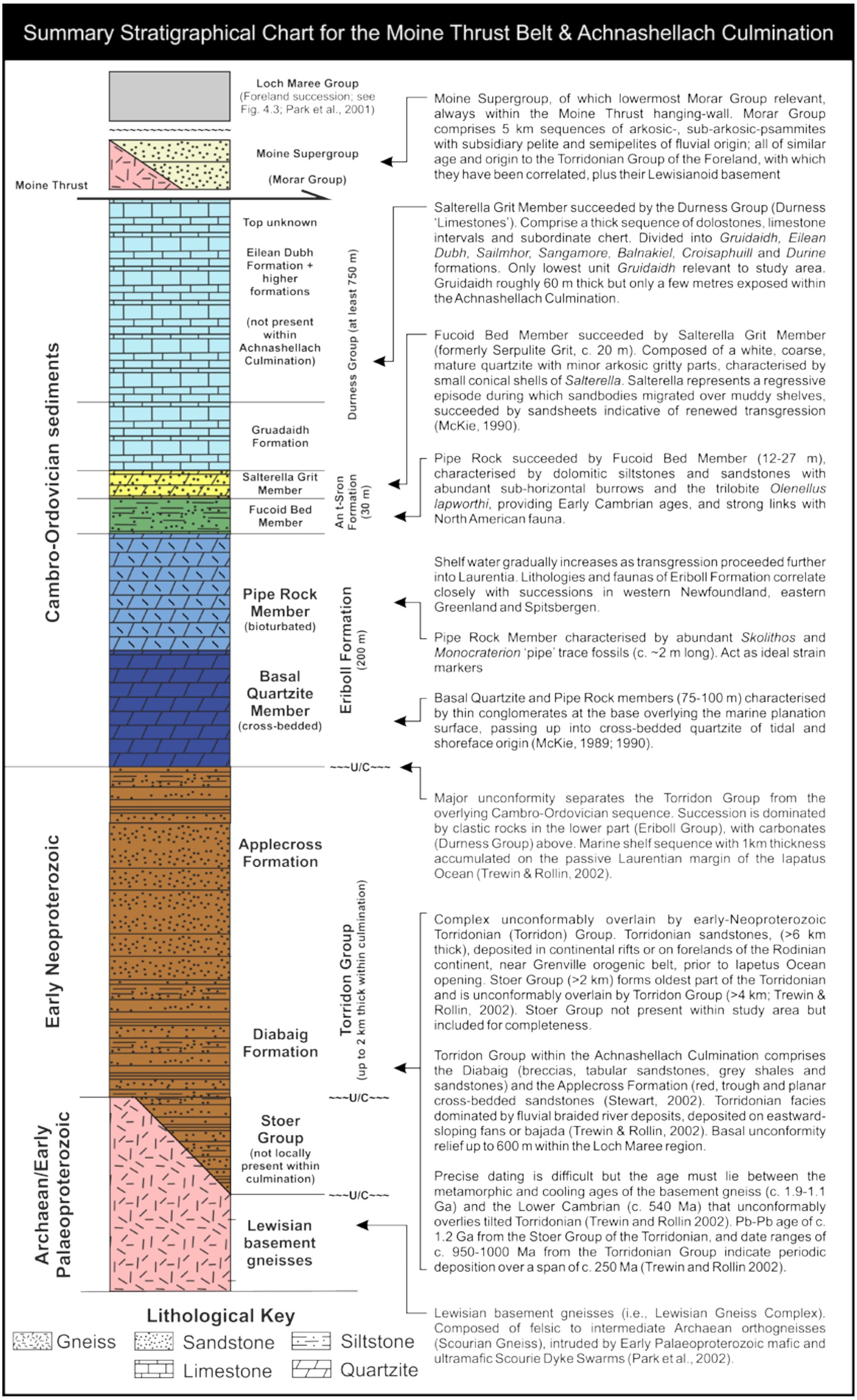


Figure 4.3: Generalised and simplified composite stratigraphical column of the units exposed within the Moine Thrust Belt and the Achnashellach Culmination. Thicknesses of An t-Sron and Eriboll Formation rocks appropriate to the Achnashellach area. These units and their deformed derivatives, comprise those identified within the Loch Maree Transverse Zone.

Parnell *et al.,* 2011). Deposition of these units is bracketed by metamorphic and cooling ages of basement gneisses (c. 1.9-1.1 Ga) and the Lower Cambrian (c. 540 Ma) in continental rifts or the continental Rodonia foreland near the Grenville orogenic belt, prior to Iapetus Ocean opening (e.g., Soper *et al.,* 1998; Stewart, 2002; Trewin & Rollin, 2002; Butler *et al.,* 2007; Krabbendam *et al.,* 2008; Krabbendam & Leslie, 2010).

Another major unconformity spanning a 400 million year hiatus separates the Torridon Group from the overlying Cambro-Ordovician succession which formed on the passive Laurentian margin of the Iapetus Ocean (Figure 4.3; McKie, 1990; Trewin & Rollin, 2002,). The lower part of this succession (i.e., the Ardvreck Group) is dominated by the Eriboll Formation, comprising the arenitic Basal Quartzite and Pipe Rock members (each seventy five to one hundred metres thick); the latter is characterised by abundant *Skolithos* and *Monocraterion* 'pipes' (c. ~2 metres long). These distinctive trace fossils form ideal strain markers (Westergard, 1931; Swett, 1969; Wilkinson *et al.,* 1975; Coward & Kim, 1981).

Eriboll quartzites are conformably overlain by the An t-Sron Formation comprising dolomitic siltstone and dolostone of the Fucoid Beds Member (twenty metres thick, Figure 4.3) and subsequently by the Salterella Grit Member (formerly Serpulite Grit, eight metres thick). These units are succeeded by the calcareous Durness Group. Total thickness of the Durness Group limestone is believed to have exceeded seven hundred fifty metres but generally only a few metres of its basal part, the Ghrudaidh Formation, are preserved within the Achnashellach Culmination and the thrust belt as a whole (Figure 4.3; Butler *et al.,* 2007). McKie (1989; 1990), Nicholson (1993), Wright & Knight (1995), Prigmore & Rushton (1999), Park *et al.,* (2001) and Armstrong *et al.,* (2006) provide detailed descriptions of the Cambro-Ordovician succession. The sub-Cambrian unconformity is a remarkably planar surface, whilst Cambro-Ordovician formations record an extremely uniform stratigraphical thickness along the two hundred kilometre strike length of the Moine Thrust Belt (Peach *et al.,* 1907; Prigmore & Rushton, 1999; Krabbendam & Leslie, 2010).

The Moine Supergroup, of which only the lowermost Morar Group is relevant within this research, is always separated from the other lithologies by the Moine Thrust. The Morar Group comprises a thick (c. five kilometre) succession of arkosic to sub-arkosic psammites with subsidiary pelite and semipelite of fluvial origin; all are of broadly similar age and origin as the Torridon Group of the Foreland, with which they have been correlated (Figure 4.3; Soper *et al.,* 1998; Krabbendam *et al.,* 2008; Bonsor *et al.,* 2010; 2012; Strachan *et al.,* 2010).

The Loch Maree Group, comprising 2.0 Ga meta-greywackes, quartzite, marble, banded iron formation and amphibolite sheets lies in the foreland to the Moine Thrust Belt on the northern and southern walls of the Loch Maree Fault (Whitehouse *et al.,* 1997; Park *et al.,* 2001; Park, 2002; Trewin & Rollin, 2002). These units have been interpreted to have developed within a collisional suture zone within a volcanic arc setting and are located within two separate belts; one northeast of Loch Maree and another at Gairloch within the Loch Maree Fault southern wall (Figure 4.3; 4.4; Park *et al.,* 2001; Park, 2002).

4.2.2. Overview of the Achnashellach Culmination: Previous research

In contrast to the northern Loch Eriboll and Assynt regions of the Moine Thrust Belt, the southern sector between Ullapool and Kishorn has received very little attention since the work of Peach *et al.,* (1907), which identified the Achnashellach Culmination in terms of imbricate thrusting with associated folding. Within the Achnashellach Culmination, more

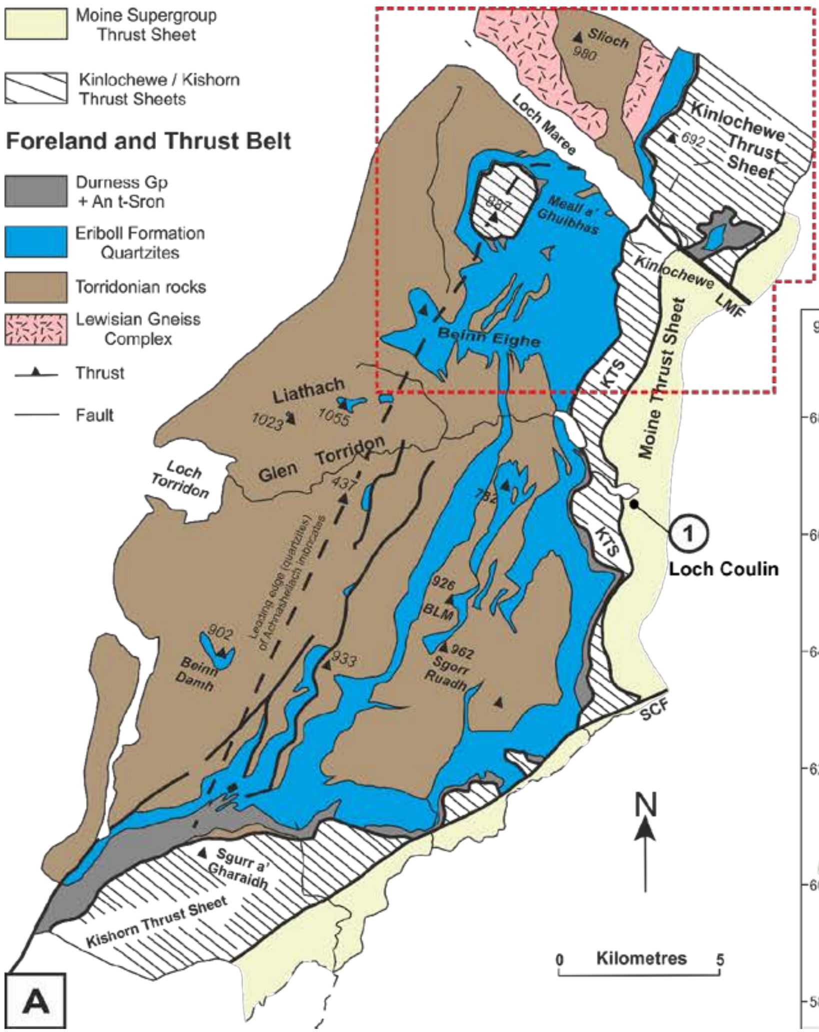
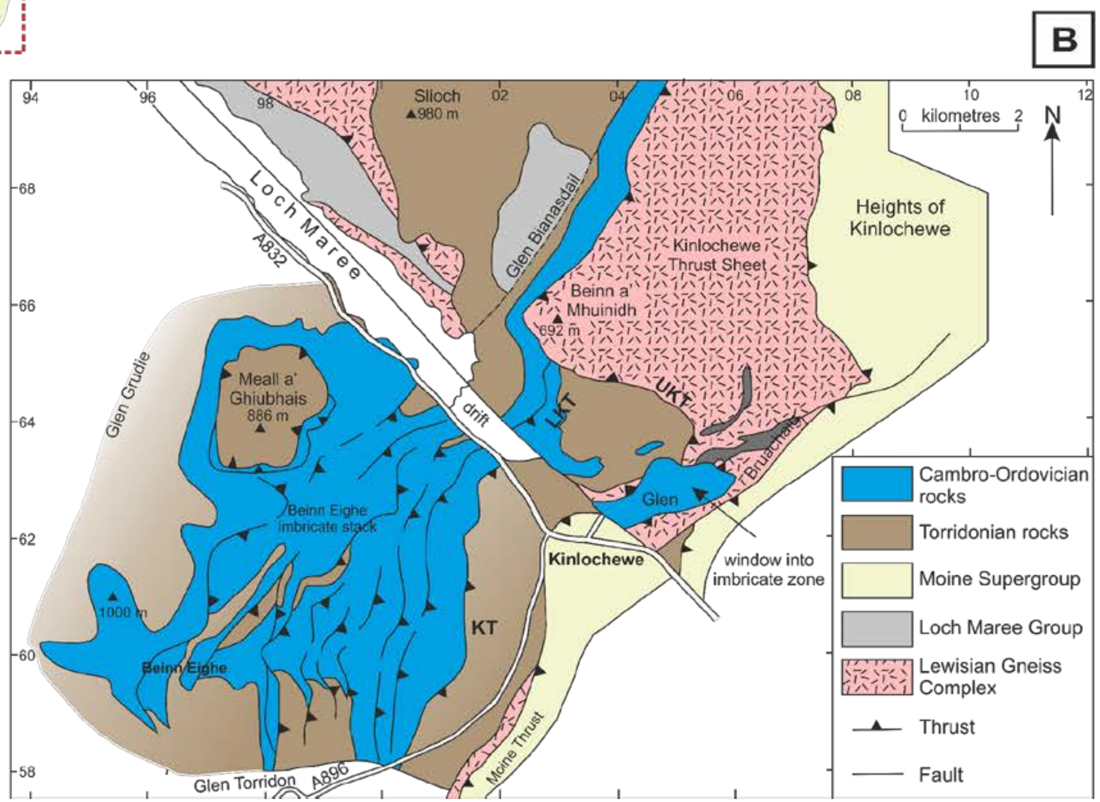


Figure 4.4: (A) Simplified geological map of the Moine Thrust Belt within the Achnashellach Culmination. Inset highlights northern section of the Achnashellach Culmination within current research **(B)**. KTS = Kishorn/Kinlcohewe thrust sheet, SCF = Strathcarron Fault (Adapted after Peach *et al.*, 1907; Butler *et al.*, 2007).

(B) Map of the Slioch-Meall a' Ghiubhais-Beinn Eighe area. KT = Kinlochewe Thrust, UKT = Upper Kinlochewe Thrust, LKT = Lower Kinlochewe Thrust (Adpated after Matthews, 1984; Butler *et al.*, 2007).



detailed work is restricted to unpublished theses (e.g., Matthews, 1984; Morgan, 1985; Cain, 2013) and reviews (e.g., Butler *et al.,* 2006; 2007; Mendum *et al.,* 2009). The Achnashellach Culmination lies between the villages of Kinlochewe (NH 0267 6200) in the north and Kishorn (NG 8343 4057) towards the south, representing a bulge or culmination within the Moine Thrust plane (Figure 4.4a). Variations in along-strike Torridon sandstone thicknesses within the Achnashellach thrust sheets and along-strike variations north to south across the Loch Maree Fault led Butler *et al.,* (2007) to be the first to infer a potential transverse zone within the Loch Maree Fault region. The following subsections within this section identify key cross-strike discontinuity phenomena presented within previous research concerning the Achnashellach Culmination.

4.2.2.1. Along-strike continuity of the Kishorn / Kinlochewe Thrust Sheet

South of the Loch Maree Fault, the Achnashellach Culmination has been characterised by Matthews (1984) and Butler *et al.,* (2007) as a medium-, to thick-skinned thrust system incorporating a map pattern of alternating Cambrian quartzites, abundant Torridonian rocks and minor basement slivers (Figure 4.4; Matthews, 1984; Butler *et al.,* 2007). Similarly to the imbricate systems of Assynt, the imbricated Cambrian strata of the southern Moine Trust Belt within the Achnashellach Culmination are not capped by the Moine Thrust itself. Rather, they are capped by an allochthonous sheet or sheets of Lewisian and Torridonian rocks forming the roof (e.g., Kishorn / Kinlochewe Thrust Sheet; Butler *et al.,* 2007; Figure 4.4a). Previous work by Matthews (1984) and reported by Butler *et al.,* (2007) within the Achnashellach Culmination has primarily focused on the along-strike continuity of the Kishorn / Kinlochewe Thrust Sheet and the development of its footwall imbricates.

Within the southern Achnashellach Culmination, the position of the Kinlochewe Thrust Sheet was interpreted by Coward & Whalley (1979) and Butler *et al.,* (2007) to be taken by the Kishorn Thrust Sheet. Butler *et al.,* (2007) suggested that prior to erosion and slip along the Strathcarron Fault these two allochthonous Precambrian units might have been continuous towards the Loch Maree Fault incorporating Torridonian lithologies (i.e., Sleat Group to Applecross Formation units; Figure 4.4a). An along-strike continuity is therefore suggested by Butler *et al*., (2007) from the Strathcarron Fault northwards across Loch Coulin (Figure 4.4a [1]) towards the Loch Maree Fault.

4.2.2.2. Beinn Eighe and Meall a' Ghiubhais massif (Loch Maree Fault southern wall)

Within the footwall of the Kishorn / Kinlochewe Thrust Sheet, footwall imbricates comprising Cambrian quartzites and Torridon sandstones are identified. Along the Beinn Eighe ridge, footwall imbricates were identified by Butler *et al*., (2007) as containing up to two kilometres of Torridonian sandstones and two hundred metres of Cambrian quartzites creating ramp-on-ramp thrust geometries which have been back-steepened (Figure 4.5a). Restored sections within Butler *et al.,* (2007) suggest total shortening of five kilometres within this section of the Achnashellach Culmination (Figure 4.5a). Furthermore, Butler *et al.,* (2007) identified a chiefly forelandward-propagating thrust system with up to three hundred metres of entrained Torridon sandstone within imbricates from Beinn Eighe north towards the Loch Maree Fault at a depth of five hundred metres (Figure 4.4b; 4.5b).

Along the southern wall of the Loch Maree Fault, northwest of Kinlochewe village, an important tectonic klippe crops out in the hill, (i.e., Meall a' Ghiubhais; Figure 4.4b; 4.45), dominated by rocks of the Applecross Formation. These units are suggested by Matthews (1984) to be underlain by tens of metres of Sleat Group that in turn locally rest unconformably on Lewisian basement. Development of the Meall a' Ghiubhais Klippe, and

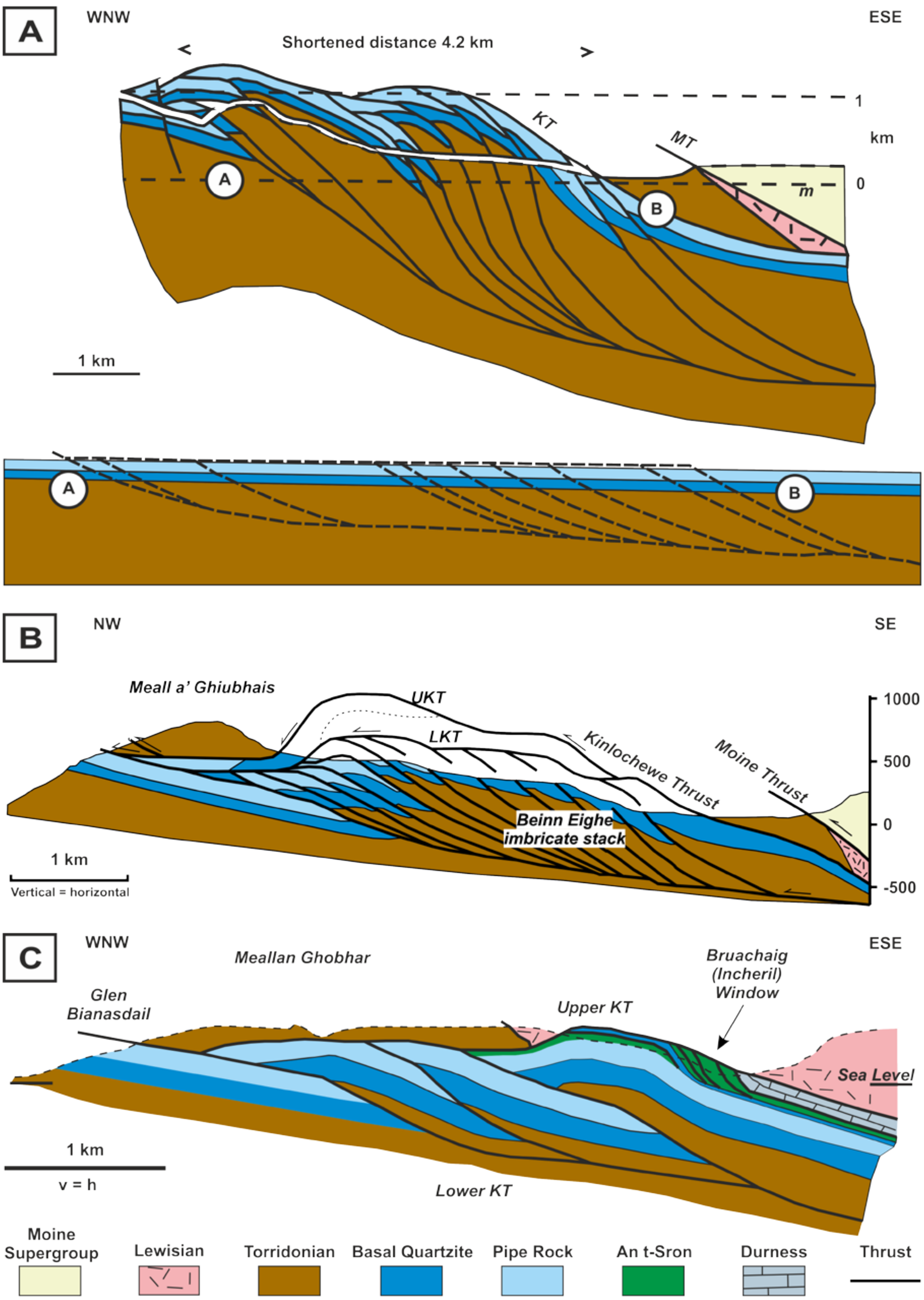


Figure 4.5: (A) Balanced and restored section through the Beinn Eighe transect. MT = Moine Thrust, KT = Kinlochewe Thrust **(B)** Cross-section through the northern part of the Achnashellach Culmination, through the Meall a' Ghiubhais klippe of the Kinlochewe Thrust. UKT = Upper Kinlochewe Thrust, LKT = Lower Kinlochewe Thrust. **(C)** Cross-section through the thrust belt on the NE side of the Loch Maree Fault, passing through the Bruachaig window suggesting a lateral continuity of thrust sheets north to south across the Loch Maree Fault. This is contested within this research (All sections adapted after Butler *et al.*, 2007).

the footwall Cambrian quartzites imbricates was suggested by Butler *et al.,* (2006; 2007) to have developed as a result of an Upper and Lower Kinlochewe Thrust Sheet, with the upper overriding the lower creating a zone of strong deformation within its footwall within the region of the klippe (Figure 4.5b). Matthews (1984) identified that all footwall imbricate units within this sector show little penetrative strain associated with thrusting; highlighted by Eriboll Formation Pipe Rock Member quartzites along *Skolithos* and *Monocraterion* ‘pipes’.

4.2.2.3. The Loch Maree Fault

Within the northern sections of the Achnashellach Culmination around the village of Kinlochewe, the culmination is transected by the Loch Maree Fault (LMF) which has been suggested by Butler *et al.,* (2007) to form the northwest boundary of the Achnashellach Culmination (Figure 4.4). The Loch Maree Fault trends west-northwest to east-northeast, sub-parallel to the transport direction, and is associated with a relatively narrow Proterozoic (Laxfordian) shear zone (Park, 2002; Figure 4.2). The Loch Maree Fault has been suggested by Coward *et al.,* (1989) to link with the Minch Fault along the Outer Isles and its associated sedimentary basins, therefore acting as a regionally dominant structure. The Loch Maree Fault has major pre-Torridon movement (slicing the outcrop of the Loch Maree Group in two) as well as post-Torridon movement which transects and displaces all thrusts up to and including the Moine Thrust (Figure 4.4b; British Geological Survey, 1999; Park, 2002; Butler *et al.,* 2007). This structure has been suggested by Butler *et al.,* (2007) to be the dominant structure creating along-strike discontinuities within the Kinlochewe region.

4.2.2.4. Heights of Kinlochewe: (Loch Maree Fault northern wall)

Within the Loch Maree Fault northern wall, Butler *et al.,* (2007) identifies an Upper and Lower Kinlochewe Thrust Sheet similar to that within the southern wall of the Loch Maree Fault (Figure 4.5b; 4.5c). In its type area, north of the eponymous village, thrust sheets dominantly consist of Lewisian basement rocks, which Butler *et al.,* (2007) places within the Upper Kinlochewe Thrust (Figure 4.4b). In this regard, it bears comparison with equivalent structures in Assynt, the Glencoul, and Ben More thrust sheets further north within the Moine Thrust Belt (Butler *et al*., 2006; 2007).

Butler *et al.,* (2006) further states that Lewisian rocks within this northern wall retain much of its foreland character, appear to have experienced very little internal deformation during west-northwest translation, and preserve small stratigraphical outliers of Torridonian rocks along the Heights of Kinlochewe. Butler *et al.,* (2006) identify Scourie dyke swarms within the Upper Kinlochewe Thrust Sheet which parallel those within the foreland, further supporting little internal deformation.

Hinterland portions of the northern wall of the Loch Maree Fault are dominated by the Bruachaig (Incheril) Window which was assigned by Butler *et al.,* (2007) to the Lower Kinlochewe Thrust Sheet (Figure 4.4b; 4.5c). The Lower Kinlochewe Thrust has been interpreted by McClay & Coward (1981) as being folded and then subsequently eroded to produce the forenamed window. The centre of the window is cored by Pipe Rock units and is rimmed by imbricates composed chiefly of Fucoid Beds and Salterella Grit (Butler *et al*., 2007). It is these An t-Sron Formation rocks that dominate the outcrop of the window. On the eastern side of the window, the footwall to the Kinlochewe Thrust lies in Durness Limestone, whilst the western side lies in Salterella Grit.

Butler *et al.,* (2007) deduced that the Upper Kinlochewe Thrust cuts down section in its footwall from east to west (Durness Limestone down to Salterella Grit), whilst the south-western edge of the window is controlled by the Loch Maree Fault and has been subsequently bulged. This was interpreted by Butler *et al.,* (2007) as being generated by imbrication of the Cambrian quartzites within the Lower Kinlochewe Thrust Sheet, leading to a shortening of about two kilometres within the northern wall.

In summary, Butler *et al.,* (2006) stated that structural styles along the Kinlochewe Thrust Sheet are highly unlikely to have been focussed along or adjacent to a reactivated pre-existing basement fault, fault zones or other inherited basement heterogeneities assuming they are the same either side of the Loch Maree Fault. This research identifies a significant cross-strike change not only across the Loch Maree Fault within the northern and southern walls, as suggested within Butler *et al.,* (2007), but a series of cross-strike discontinuities from the Beinn Eighe Massif (Loch Maree Fault southern wall) to the Heights of Kinlochewe (Loch Maree Fault northern wall).

4.3. Achnashellach Culmination fault network analysis: LMTZ identification

Regional analyses of the Loch Maree Transverse Zone (LMTZ) within the northern sections of the Achnashellach Culmination began by determining the areal extent of the LMTZ within the Achnashellach Culmination. A detailed fault network analysis of the whole Achnashellach Culmination was undertaken to identify along-strike oblique / transport lateral structures (Figure 4.6). The culmination was subdivided into domains (i.e., southern, central and northern) along a series of potential transverse structures highlighted within the fault network analysis. The northern domain, comprising the LMTZ, is the primary focus of this research and is divided into the Beinn Eighe and

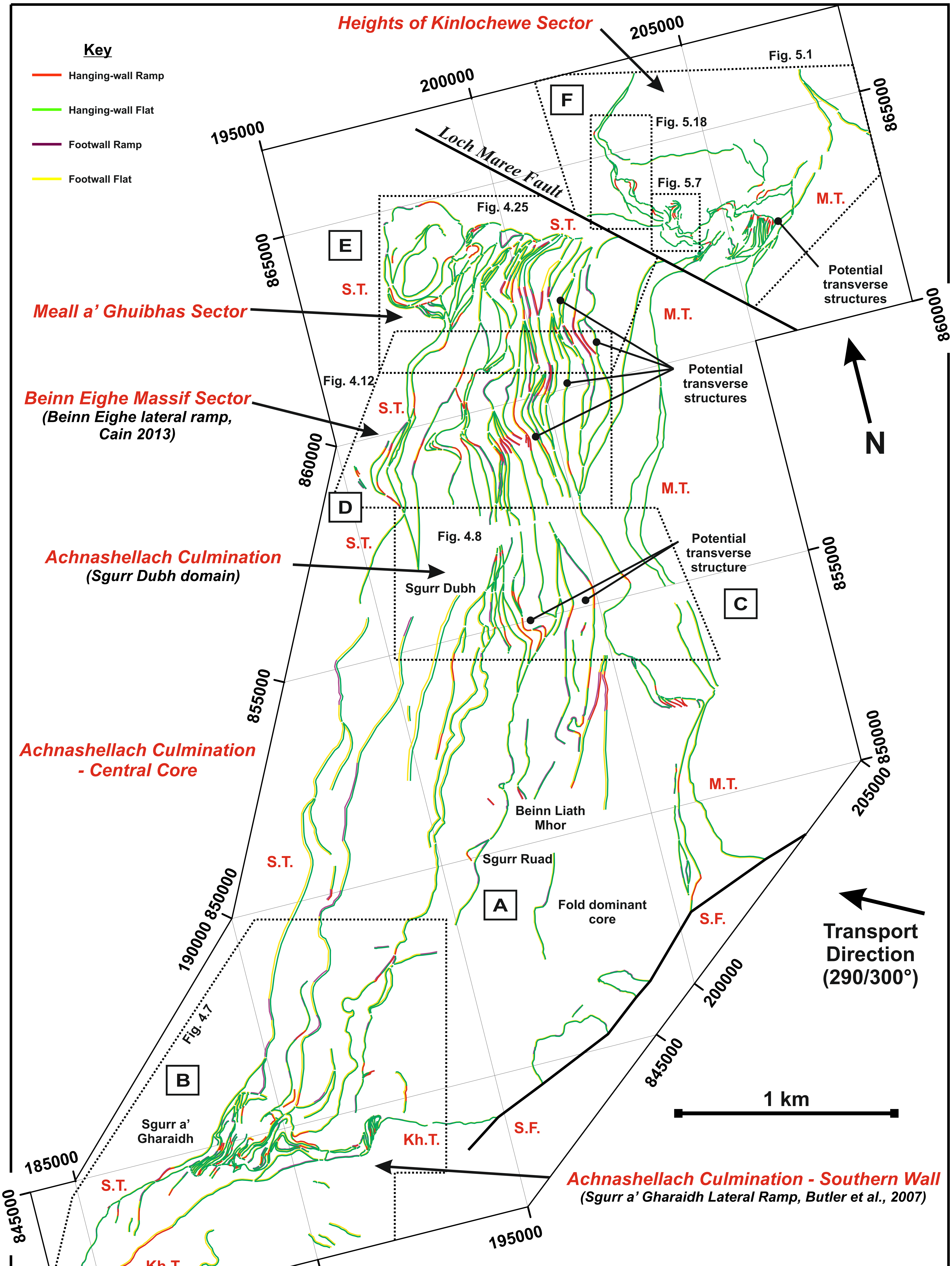


Figure 4.6: Regional fault network analysis of the Achnashellach Culmination highlighting potential transverse structures. Observations indicate a fold dominant central core bounded by fold-thrust dominant northern and southern walls. Individual fault network analysis plates are highlighted. Kh. T. = Kishorn Thrust, M.T. = Moine Thrust, S.T. = Sole Thrust, S.F. = Strathcarron Fault.

Meall a' Ghiubhais sectors comprising the southern wall of the LMTZ, whilst the Heights of Kinlochewe sector comprises the LMTZ northern wall (Figure 4.6).

4.3.1. Achnashellach Culmination: Central core domain

The Achnashellach Culmination central core is composed of a fold-dominant domain with only a few dominant thrust faults continuing along-strike [NG 9500 5000] hundreds of metres apart (Figure 4.6a). Thrusts within this domain are folded and typically demonstrate flat-on-flat relationships with only minor hanging-wall ramps present along major hills including, Sgurr Ruad [NG 9577 5062] and Beinn Liath Mhor [NG 9677 5191] (Figure 4.6a). This indicates a dominance of ductile deformation, rather than brittle thrust nucleation within the core during development of the culmination, supporting observations of Butler *et al.,* (2007). However, this structural style alters towards the southern and northern extremes of the central domain where several major thrusts coalesce (Figure 4.6b; 4.6c).

4.3.2. Achnashellach Culmination: Southern bounding lateral ramp (Sgurr a' Gharaidh)

The Achnashellach Culmination southern tip [NG 9000 4500] (Figure 4.6b; 4.7a) comprises a lateral structure based within Eriboll Formation quartzites and An t-Sron Formation lithologies stretching from Cnoc na Cùile [NG 9224 4518], across Coire Mhic Fhearghais [NG 9131 4562] and Cnoc Glas [NG 8981 4592], terminating at Coille Dhubh [NG 8778 4523]; identified by Butler *et al.,* (2007) as the Sgurr a' Gharaidh imbricate stack within the Kishorn Thrust footwall. Along this transect line many short transport-parallel (i.e., lateral) hanging-wall ramps are observed (Figure 4.7b [1]), whilst further north predominant frontal footwall and hanging-wall ramps are identified (Figure 4.7b [2]). Hanging-wall and footwall ramp observations within the fault network analysis support

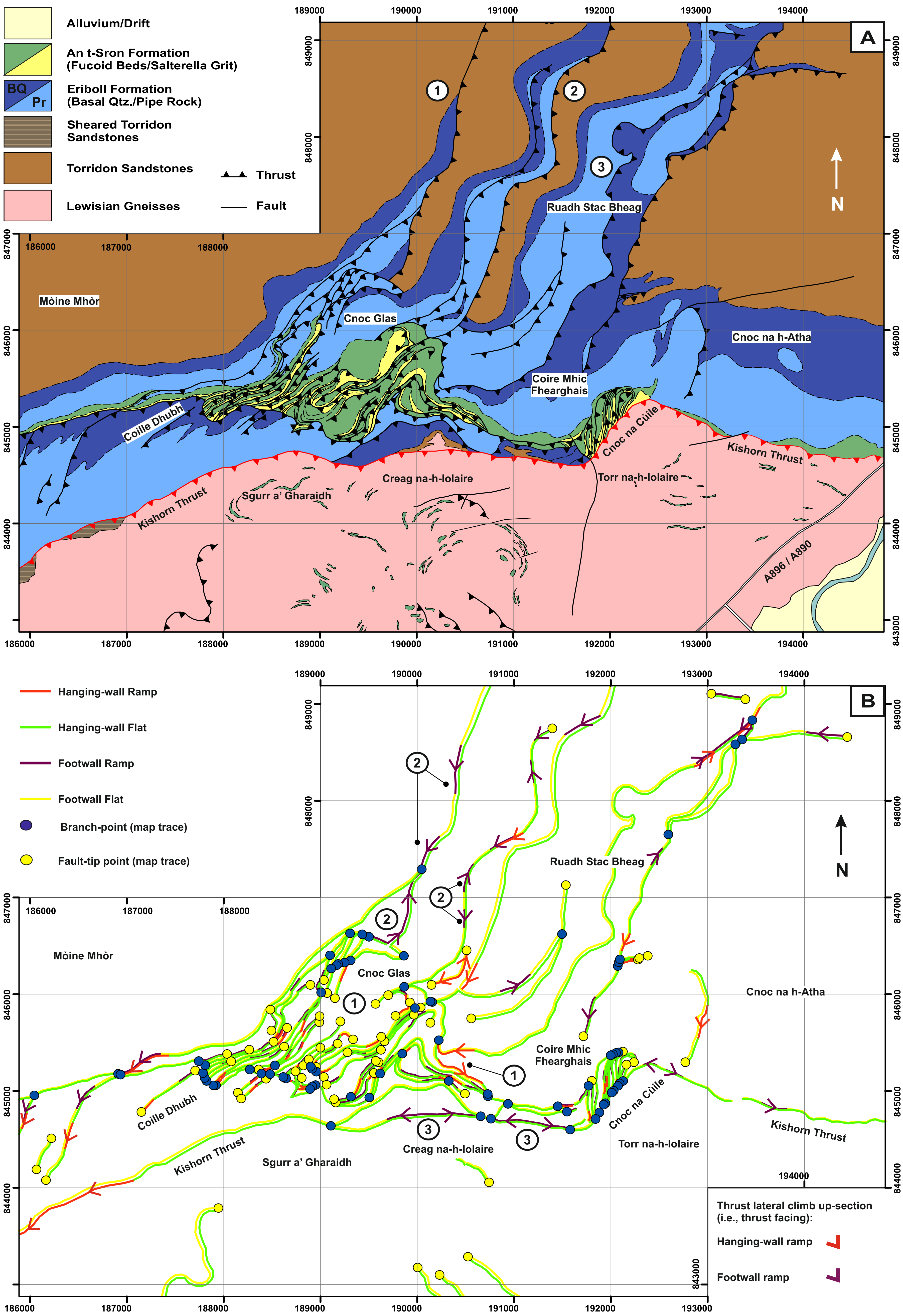


Figure 4.7: (A) Geological map of the southern Achnashellach Culmination. A dominant structure is observed within Eriboll quartzites and An t-Sron Formation lithologies within the Kishorn Thrust footwall (i.e., the Sgurr a' Gharaidh lateral ramp) from Cnoc na Cùile [NG 9224 4518] across Coire Mhic Fheraghais [NG 9131 4562] and Cnoc Glas [NG 8981 4592] to Coille Dhubh [NG 8778 4523]. Kishorn Thrust (red). **(B)** Fault network analysis of the Sgurr a' Gharaidh lateral ramp. Numerous hanging-wall and footwall ramps indicate a multiphase deformation history within the southern Achnashellach Culmination. Branch-line and fault-tip line analyses indicate a dominant thrust nucleation and termination zone as a result of along-strike lithological changes creating this lateral ramp. Thrust facing directions within the hanging-wall and footwall are indicated along dominant thrusts.

observations by Butler *et al.,* (2007), identifying a multiphase deformation structure, with localised folding and out-of-sequence thrusting causing hanging-wall and footwall deformation resulting from along-strike lithological changes (i.e., thick Eriboll quartzites against thinly bedded An t-Sron units) and later movement phases along the Kishorn Thrust (Figure 4.7b [3]).

High density clustering of branch- and tip-points within the fault network analyses along map-trace thrusts indicate that this region acted as a thrust nucleation and termination point bounding the southern extremes of the Achnashellach Culmination, along which only three dominant thrusts continue northwards (Figure 4.7a [1, 2, 3]; 4.7b). This structure is interpreted as an unbreached lateral ramp / culmination wall within the fault network analysis, formed as a result of the interaction of more thinly bedded Cambro-Ordovician lithologies comprising the southern wall of the culmination, and Lewisian basement within the Kishorn Thrust hanging-wall. Lewisian basement protrudes further to the north-west within this section of the Moine Thrust Zone acting as a bounding wall for the culmination.

4.3.3. Achnashellach Culmination: Northern edge of central domain (Sgurr Dubh)

The northern wall of the central core along Sgurr Dubh [NG 9855 9557] south of the Beinn Eighe Massif differs greatly in structural style (Figure 4.8a). Whilst thrusts coalesce similar to the southern culmination tip, thrusts are more spaced out (300m compared with tens of metres in the south). This is as a result of dominant Torridonian and Eriboll Formation lithologies within the northern wall in comparison to dominant An t-Sron Formation lithologies in the south which are more thinly bedded and fissile. Within the Sgurr Dubh hillside, dominant hanging-wall frontal and oblique thrust ramps cutting up-stratigraphical section southwards, are viewed indicating a deformed zone of folded Eriboll quartzites and Torridon sandstones (Figure 4.8a [1]; 4.8b [1]). This is interpreted as a response to

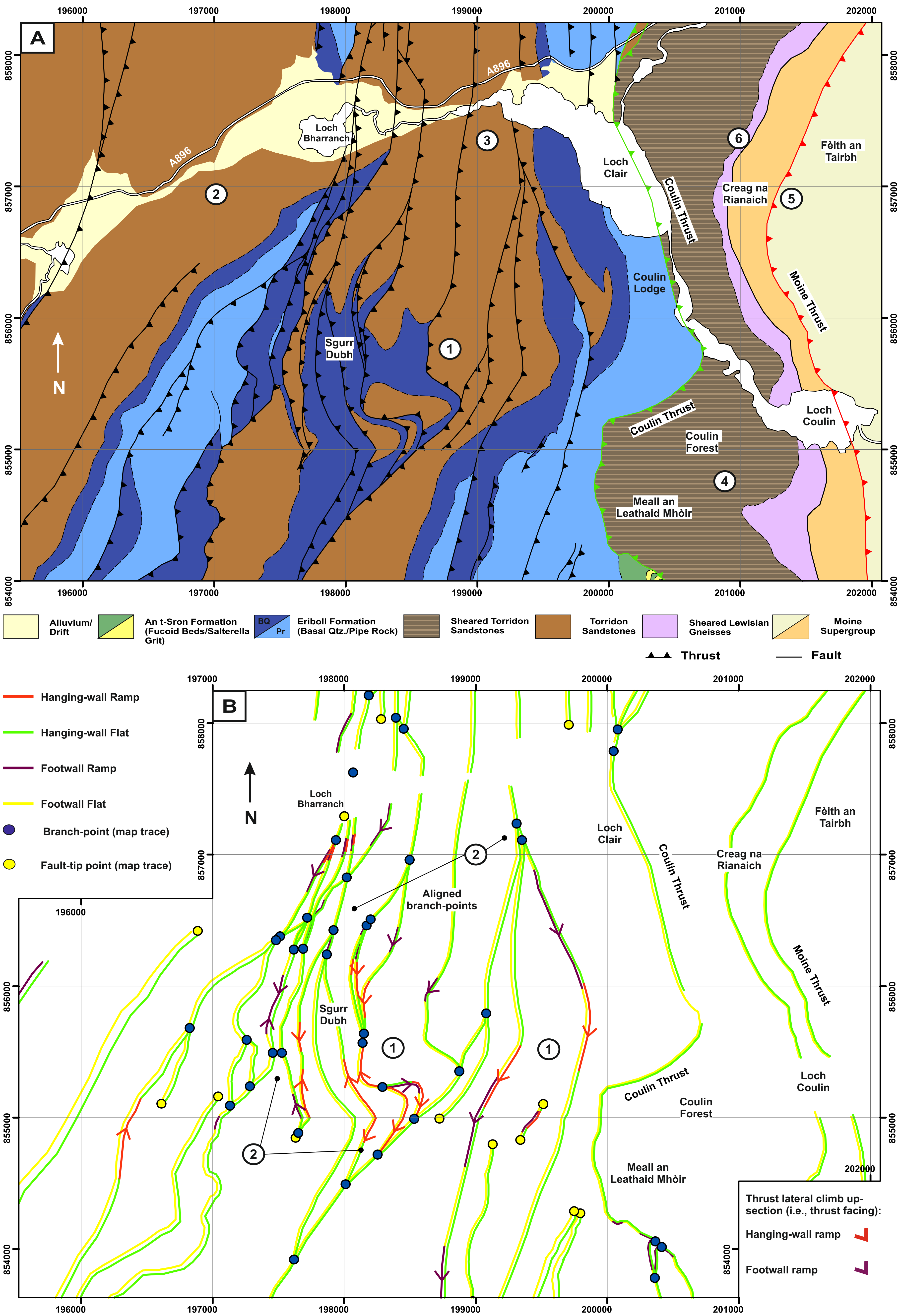


Figure 4.8: (A) Geological map of the Achnashellach Culmination central domain northern edge along Sgurr Dubh [NG 9557 5500]. Thrust map-traces coalesce within this region comprising Eriboll quartzites and Torridon sandstones which have deformed. Development of newly identified Coulin thrust sheet also identified (green thrust plane). **(B)** Fault network analysis of the Sgurr Dubh region. Hanging-wall ramps (1) and branch-point map-trace alignments (2) support observations by Cain (2013), identifying along-strike deformations associated with a forelandward change from 300 m Torridon imbricates, to a package of 1 km Torridon (i.e., a raised horst block) south of the Beinn Eighe Massif. Thrust facing indicates a dominant southward climb within undeformed hinterland thrusts.

two distinctly different Torridon sandstone packages, the first one kilometre thick, comprising a raised horst block within the pre-thrust template (Cain, 2013; Figure 4.8a [2]); the second comprising three hundred metre imbricates (Figure 4.8a [3]). Branch-points along the map-traces of these thrust ramps are aligned sub-parallel to regional transport (i.e., 290 / 300°; Figure 4.8b [2]) identifying the southern edge of the suggested horst block and its subsequent along-strike deformations during thrust propagation and culmination development.

Hinterlandward of this structure, the new Coulin Thrust and its respective thrust sheet also nucleate further supporting along-strike differential responses to structures within the foreland during allochthon formation (Figure 4.8b [4]). The major focus of this research resides within the northern domain comprising the Beinn Eighe and Meall a' Ghiubhais sectors (Figure 4.6d; 4.6e) across the Loch Maree Fault into the Heights of Kinlochewe sector (Figure 4.6f). These sectors, comprising the Loch Maree Transverse Zone (LMTZ), identify a series of cross-strike discontinuities which are described individually in greater detail in the following sections supported by geometrical and kinematic observations.

4.4. Thrust architecture south of Loch Maree Transverse Zone: Southern Loch Maree Fault sidewall

The southern sidewall of the Loch Maree Transverse Zone (LMTZ) is dominated by the Kinlochewe Thrust Sheet and its footwall imbricates which compose the Beinn Eighe and Meall a' Ghiubhais sectors (Figure 4.1). Footwall imbricates are dominated by Eriboll Formation quartzites and varying lateral thicknesses of Torridonian sandstones. The Kinlochewe Thrust, which acts as the roof-thrust to these footwall imbricates, carries undeformed Torridonian sandstones. These are structurally overridden by sheared sandstones (Coulin Thrust Sheet) and psammites / semi-pellites (Moine Supergroup) within the Moine Thrust hanging-wall (Figure 4.1).

4.4.1. Beinn Eighe Massif Sector

Within the Beinn Eighe sector hinterland lies the Moine Thrust Sheet. The sheet is composed of Morar Formation (Moine Supergroup) psammites and semi-pellites with the Moine Thrust structurally at its base. Highly foliated meta-sedimentary units present within the Moine Thrust Sheet above Creag na Rianaigh [NH 0112 5694] highlight crenulation cleavage deformation structures depicting lateral shortening and thrust translation over a variety of scales (metres to centimetres) (Figure 4.8a [5]; 4.9). Crenulation folding within this section of the Moine Thrust Sheet show minor recumbent folding indicating a top-to-the-west-northwest to northwest thrust translation (290 / 300°N). These results within the Beinn Eighe sector support previous interpretations of transport within this section of the Moine Thrust Belt (e.g., Johnson, 1958). Evidence of localised thrusting within calcareous lithologies along the map-trace of the Moine Thrust Sheet are also viewed within this portion of the Moine Thrust Belt creating localised 'sink-hole' localities (e.g., NH 0121 5682).

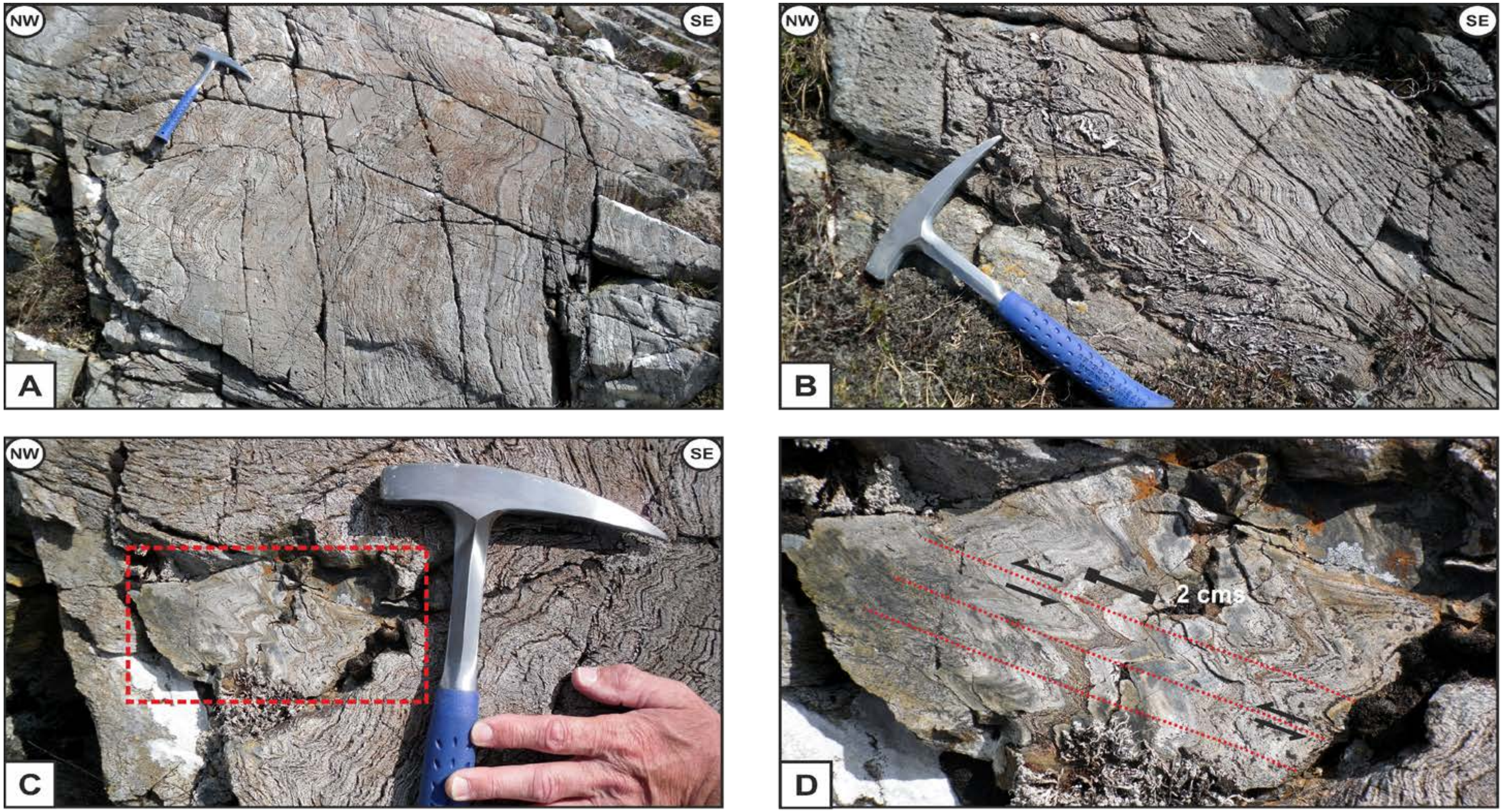


Figure 4.9: Moine Supergroup (Morar Formation) psammites and semi-pelites displaying crenulation folding over a variety of scales from metres **(A)** to centimetre **(B)** scales. **(C)** Internally these crenulation folds indicate internal shearing over centimetre scales **(D)**. This indicates a top-to-the-WNW/NW (290/300°N) thrust transport direction for the underlying Moine Thrust within the hinterland portions of the Beinn Eighe region within the Moine Thrust Belt. (Scale: Hammer = 30 cm).

Structurally underlying the Moine Thrust lies the newly interpreted Coulin Thrust Sheet (so named after its type locality at Loch Coulin [NH 0142 5526]). The Coulin Thrust Sheet had previously been incorporated within the Kinlochewe / Kishorn Thrust Sheet as Sleat Group lithologies (e.g., Butler *et al.,* 2006; 2007). The Coulin Thrust Sheet is characterised by sheared Torridonian sandstone units and elements of sheared gneisses (Figure 4.10; 4.11a.). Supportive evidence of the regional transport direction (290 / 300°N) can also be identified within the Coulin Thrust Sheet at Creag na Chuichinn [NH 0096 5728] (Figure 4.8a [6]). Sheared 'pips' of gneiss within the hinterland sections of the thrust sheet are incorporated within the sheared Torridonian sandstone units forming small 'sheath' folds, orientated strike-parallel to the regional transport direction (Figure 4.11b; 4.11c). These structures vary in size within the Moine Thrust Zone (e.g., Alsop & Holdsworth, 1999); however, within this section of the Beinn Eighe hinterland they are seen over metre-scales. No evidence for thrusting is identified underlying the Lewisian gneiss lenses within the section until the Coulin Thrust (*senso stricto*) is reached.

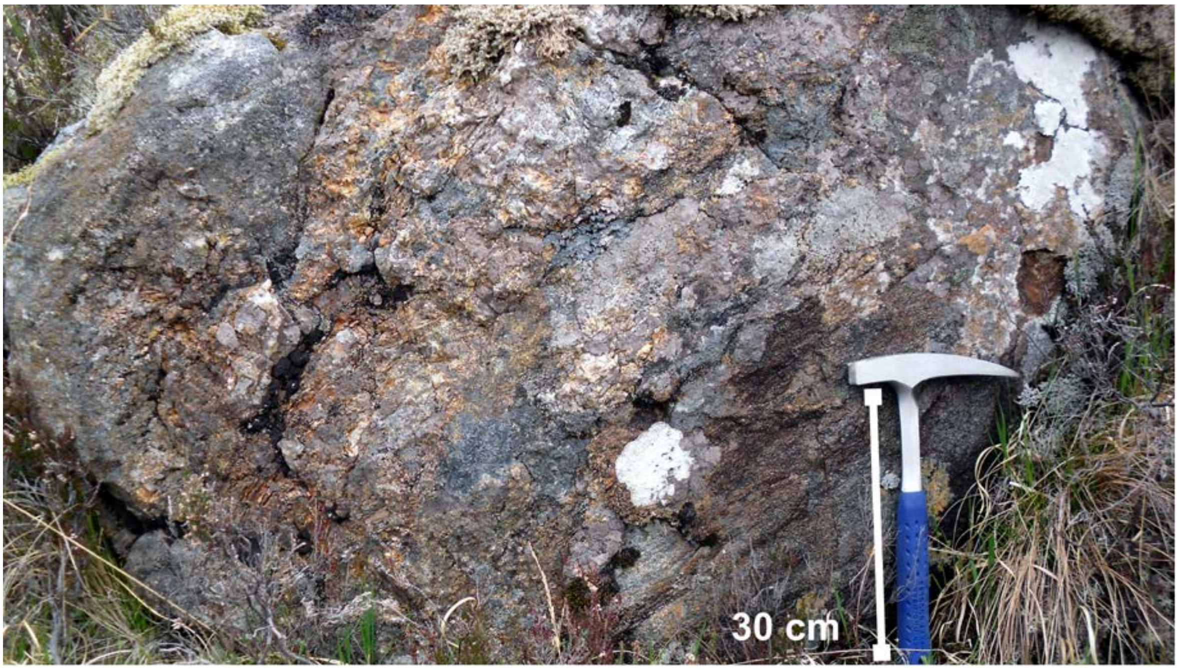


Figure 4.10: Sheared Torridonian sandstones comprising the Coulin thrust sheet. These units had previously been interpreted as Sleat Group lithologies within Butler *et al*., (2006; 2007). Hammer provided for scale.

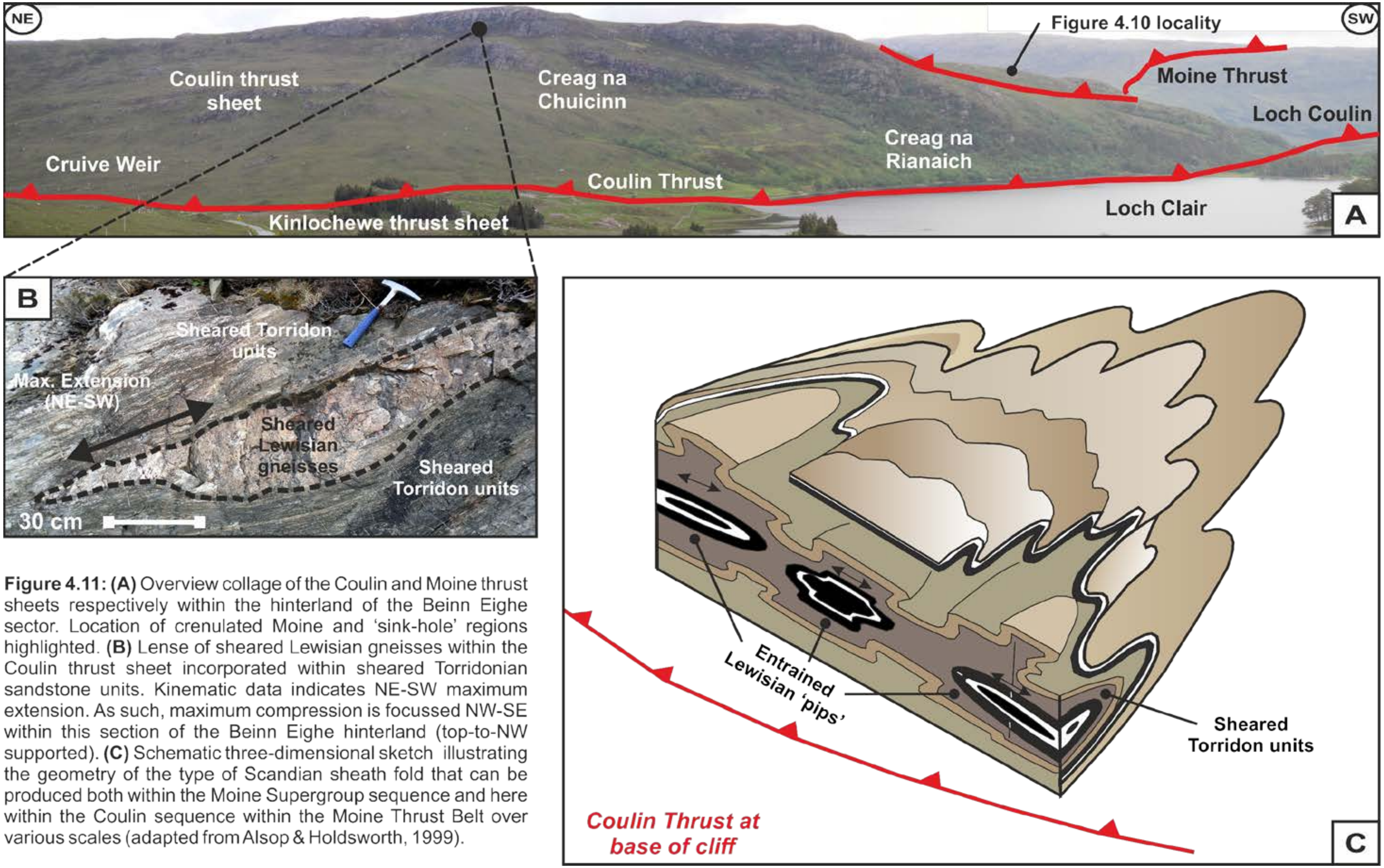


Figure 4.11: **(A)** Overview collage of the Coulin and Moine thrust sheets respectively within the hinterland of the Beinn Eighe sector. Location of crenulated Moine and 'sink-hole' regions highlighted. **(B)** Lense of sheared Lewisian gneisses within the Coulin thrust sheet incorporated within sheared Torridonian sandstone units. Kinematic data indicates NE-SW maximum extension. As such, maximum compression is focussed NW-SE within this section of the Beinn Eighe hinterland (top-to-NW supported). **(C)** Schematic three-dimensional sketch illustrating the geometry of the type of Scandian sheath fold that can be produced both within the Moine Supergroup sequence and here within the Coulin sequence within the Moine Thrust Belt over various scales (adapted from Alsop & Holdsworth, 1999).

The Coulin Thrust Sheet is structurally underlain by the Kinlochewe Thrust Sheet comprising undeformed, predominantly Applecross Formation, Torridonian sandstone units into the forelandward sections of the Beinn Eighe sector. Within the Loch Coulin region the Kinlochewe Thrust is cut out by the structurally higher Coulin Thrust (Figure 4.1). Outcrop widths of Torridonian Applecross within the Loch Coulin region only reach one hundred twenty to one hundred eighty metres within the Beinn Eighe sector. This is in stark contrast to the thickness of the Kinlochewe Thrust Sheet within the Meall a' Ghiubhais sector (1.26 kilometres map-trace at its widest; Figure 4.1). This suggests a potential later phase of movement along the Coulin Thrust truncating the underlying Kinlochewe Thrust Sheet. Within the footwall of the Kinlochewe Thrust, imbricates composed of Torridonian sandstones and Eriboll Formation quartzites dominate the southern and northern wall of the Beinn Eighe sector (i.e., the Beinn Eighe Massif). The Kinlochewe Thrust Sheet carrying undeformed Torridonian sandstones acts as its 'roof' thrust.

The Beinn Eighe Massif is comprised of two distinct ridges and corresponding coires. From hinterland to foreland the southern ridge line comprises Sgurr nam Fhir Duibhe [NG 9814 6004], Sgurr Ban [NG 9747 6003], Spidean Coire nan Clach [NG, 9682 5952], Còinneach Mhor [NG 9468 6004], and Sail Mhor [NG 9377 6055]. The northern ridge is comprised of Creag Dhubh [NG 9856 6079], Leathad Buidhe [NG 9880 6120], Au Ruadh-stac Beag [NG 9729 6137] and Ruad-stac Mòr [NG 9513 6115] (Figure 4.12a). Detailed work by Cain (2013) within the Beinn Eighe Massif is expanded upon and placed within the context of along-strike development of the Loch Maree Transverse Zone (LMTZ).

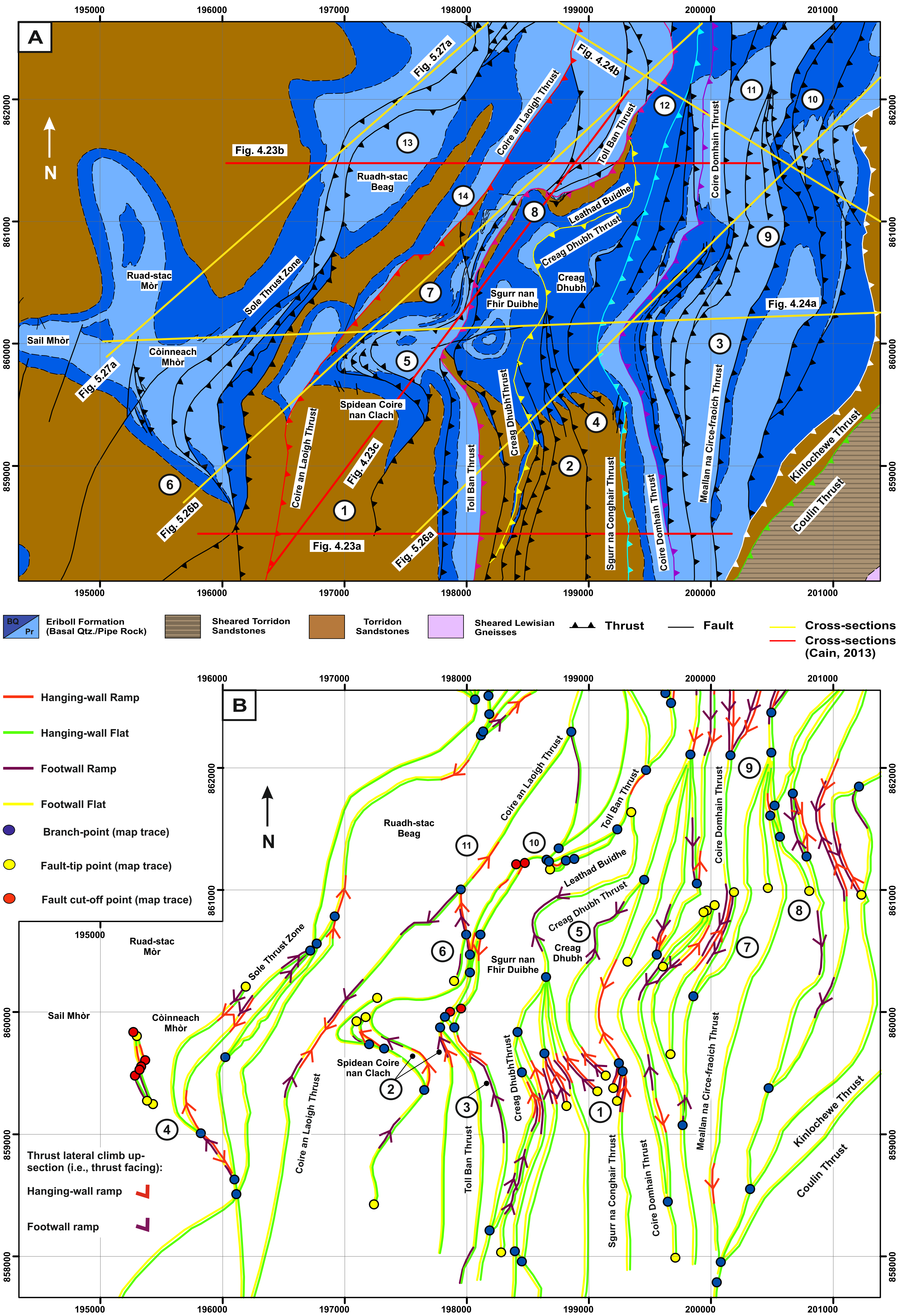


Figure 4.12: (A) Geological map of the Beinn Eighe Massif, identifying a cross-strike discontinuity within Torridonian units from the southern to northern walls. Distinct thrust map-traces also greatly differ south to north, with thrusts coalescing along the Beinn Eighe ridge to form only a few dominant thrusts within forelandward sections of the northern wall. Observations highlighted within the text are numbered. **(B)** Fault network analysis of the Beinn Eighe Massif. Distinct alignments of thrust ramps within the Beinn Eighe Massif southern wall are identified, whilst transport sub-parallel alignments of branch-point and fault-tip points within the northern wall highlight a potential sub-decollement structure. Observations highlighted within the text are numbered.

4.4.1.1. Beinn Eighe Massif southern wall: Sgurr nam Fhir Duibhe to Sail Mhor

The southern wall of the Beinn Eighe Massif comprising Sgurr nam Fhir Duibhe [NG 9814 6004], Sgurr Ban [NG 9747 6003], Spidean Coire nan Clach [NG 9682 5952], Còinneach Mhor [NG 9468 6004], and Sail Mhor [NG 9377 6055] is composed of a series of north-south orientated thrusts, displaying only minor deviations; cutting-up stratigraphical section from Torridonian sandstones to Eriboll Formation (Pipe Rock Member) quartzites (Figure 4.12a; 4.12b; 4.13a). North-south striking thrusts originate from two distinctly different structural packages of Torridonian sandstones and Eriboll Formation quartzites identified north of Sgurr Dubh [NG 9826 5841]:

1. Coire an Laoigh structural package: c. ~1 kilometre thick sequence of Torridonian sandstones south of Spidean Coire nan Clach [NG 9682 5952] within the Coire an Laoigh Thrust hanging-wall (Cain, 2013; Figure 4.12a [1]; 4.13b [1]),

2. Toll Ban / Creag Dhubh structural package: Torridonian package of thrust sheets within the hanging-walls of the Toll Ban and Creag Dhubh thrusts, comprising repetitions of thinner Torridonian sandstone thrust imbrications of up to 300 m southeast of Sgurr nan Fhir Duibhe [NG 9814 6004] (Cain, 2013; Figure 4.12a [2]; 4.13b [2]).

Lithologies within both the Coire an Laoigh and Toll Ban / Creag Dhubh structural packages are characterised by right-way-up successions of Torridonian sandstones and Eriboll Quartzites (dominated by the Basal Quartzite Member). Torridonian sandstone units display perfectly preserved pre-diagenetic dewatering and slump structures (Figure 4.14a-c), whilst Eriboll Basal Quartzites display undisturbed cross-bedding (Figure 4.14d; 4.14e). Observations indicate that little internal deformation has occurred along the thrust ramps during shortening of the thrust system. However, lithological dips within hinterlandward imbricates are characterised by steeply-dipping units (40 to 55°), whilst forelandward units closely resemble the foreland regional foreland dip (10 to 22°).

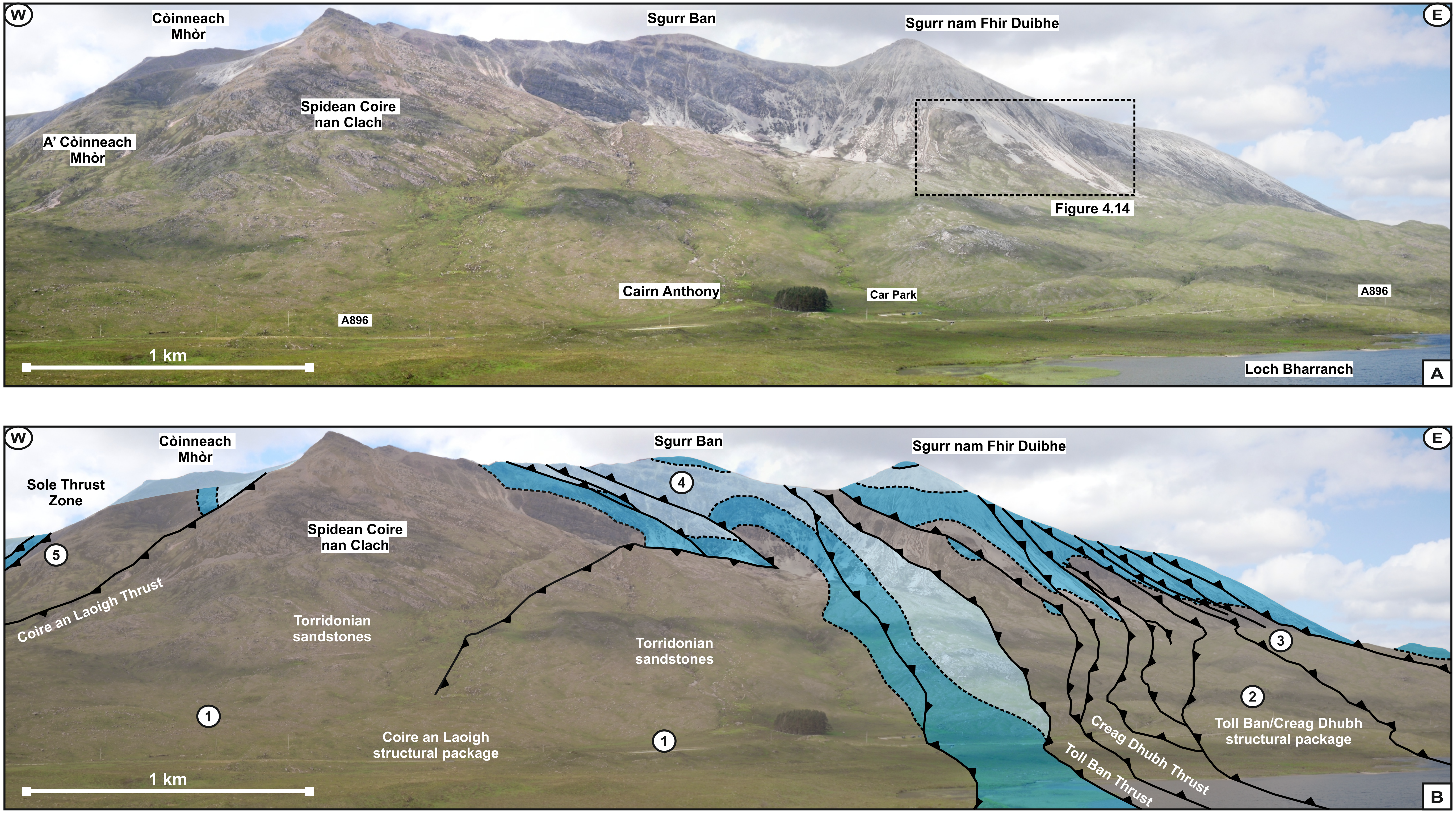


Figure 4.13: (A) Beinn Eighe Massif southern wall comprising Sgurr nan Fhir Duibhe [NG 9814 6004], Sgurr Ban [NG 9747 6003], Spidean Coire nan Clach [NG 9682 5952], Còinneach Mhòr [NG 9468 6004], and Sail Mhòr (out of image, [NG 9377 6055]. Southern wall is comprised of north-south orientated thrusts within a NW-vergent thrust system.

(B) Geological overlay within the southern wall of the Beinn Eighe Massif. Two distinct structural packages (Coire an Laoigh [1] and Toll Ban/Creag Dhubh [2]) are identified. Thrusts cut stratigraphically upwards from Torridonian sandstones to Eriboll Formartion quartzites. Distinct hanging-wall and footwall ramp geometries are identified within the fault network analysis including ramp-on-ramp geometries [3] and thrusts displaying large stratigraphical separations along-strike, such as the Toll Ban Thrust and its footwall splays [4]. Sole Thrust Zone is also identified between Spidean Coire nan Clach and Còinneach Mhòr [5].

Key

BQ / Pr — **Eriboll Formation (Basal Qtz./Pipe Rock)**

Torridon Sandstones

Thrust

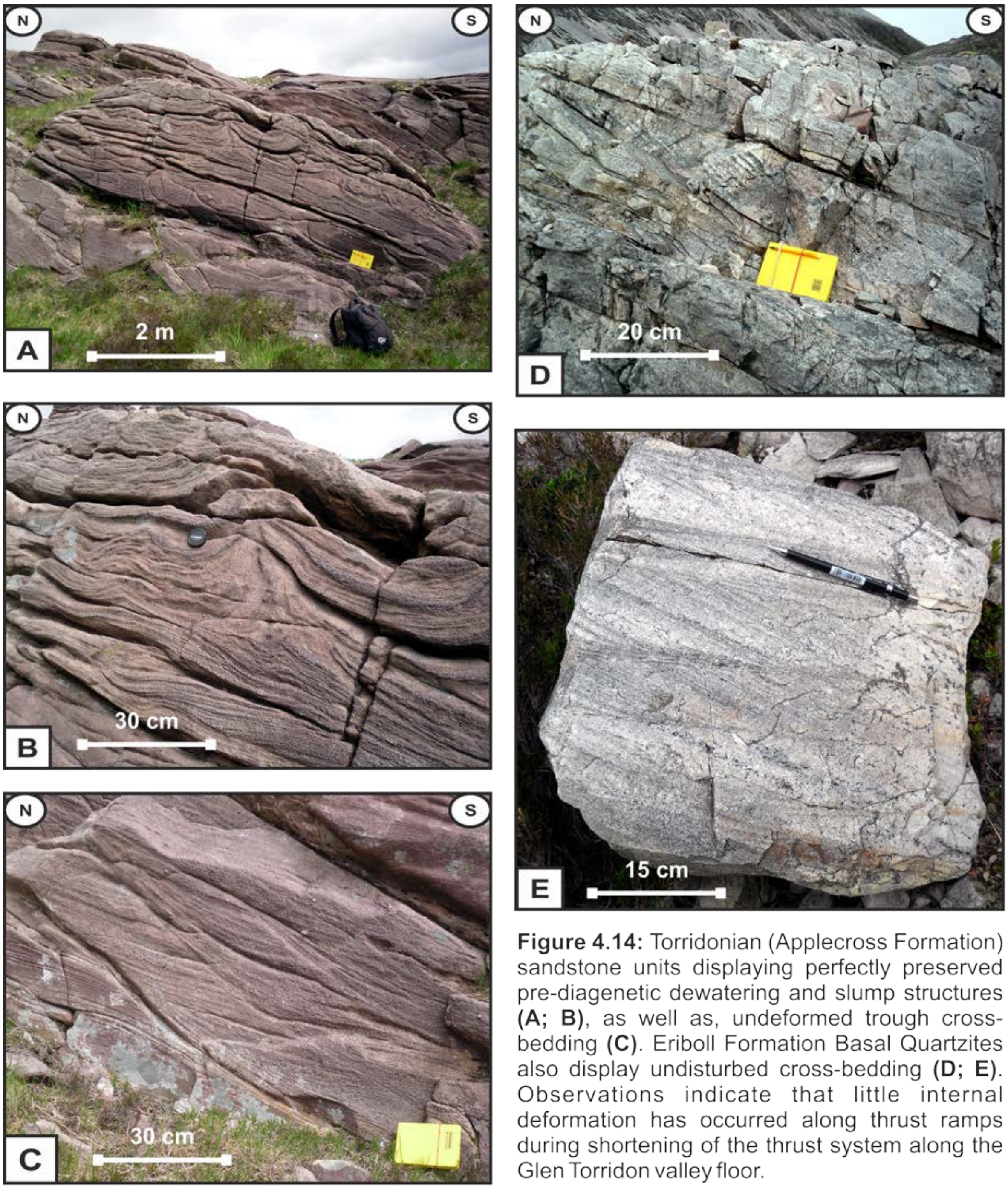


Figure 4.14: Torridonian (Applecross Formation) sandstone units displaying perfectly preserved pre-diagenetic dewatering and slump structures **(A; B)**, as well as, undeformed trough cross-bedding **(C)**. Eriboll Formation Basal Quartzites also display undisturbed cross-bedding **(D; E)**. Observations indicate that little internal deformation has occurred along thrust ramps during shortening of the thrust system along the Glen Torridon valley floor.

Thrust map-trace populations dramatically decrease towards the foreland Sole Thrust Zone as thrusts propagate from Eriboll Formation dominant thrust sheets (i.e., Sgurr na Conghair, Corie Dohmain and Meallan na Circe-fraoich thrust sheets; Figure 4.12a [3]) through the different Torridonian structural packages within a WNW-NW vergent thrust system placing Torridonian sandstones on top of Eriboll Formation quartzites (Figure 4.12a; 4.13b). Fault network analyses along the Beinn Eighe southern wall identify several distinct thrust ramps aligned sub-parallel to the regional (290 / 300°) transport direction (i.e., lateral ramps; Figure 4.12b [1, 2, 3]; 4.13b [3, 4]). These observations are further supported by map-trace analyses of branch-lines and fault-tips which also indicate thrust branch, nucleation and termination points aligned sub-parallel to regional transport (Figure 4.12b [1, 2]).

Within the Beinn Eighe southern wall hinterland southeast of Sgurr nam Fhir Duibhe [NG 9879 5949], tightly clustered hanging-wall and footwall ramp-on-ramp geometries are observed (Figure 4.12a [4]; 4.12b [1]; 4.13b [3]). Ramp-on-ramp geometries develop from a series of seven thrust splays which branch off the Creag Dhubh Thrust, all of which display only small amounts of displacement (ten to twenty metres) (Figure 4.13a; 4.15a; 4.15b). Splays show significant back-steepening from 43° to 58° cutting down stratigraphically towards the hinterland reducing the amount of Eriboll Formation (Basal Quartzite Member) within them; creating both a hanging-wall and footwall ramp profile within the fault network analysis (Figure 4.12a [3]; 4.12b [1]; 4.15b).

Within the Toll Ban Thrust hanging-wall and footwall, a series of thrust ramps dominate the Spidean Coire nan Clach region (e.g., NG 9766 5958; Figure 4.12a [5]; 4.12b [2]; 4.13b [4]). These thrust ramps identified within the fault network analysis comprise several thick, dominant thrust sheets composed of Torridonian sandstones and Eriboll Formation Basal Quartzites which have been identified by Cain (2013) to have significant stratigraphical separation along-strike within their hanging-walls and footwalls, an observation supported here through production of large hanging-wall and footwall ramps (Figure 4.12b [3]; 4.14b). The Sole Thrust is observed gradually cutting down the Beinn Eighe southern wall, geometrically and stratigraphically, between Spidean Coire nan Clach [NG 9682 5952] and Còinneach Mhor [NG 9468 6004] as a diffuse zone of Eriboll

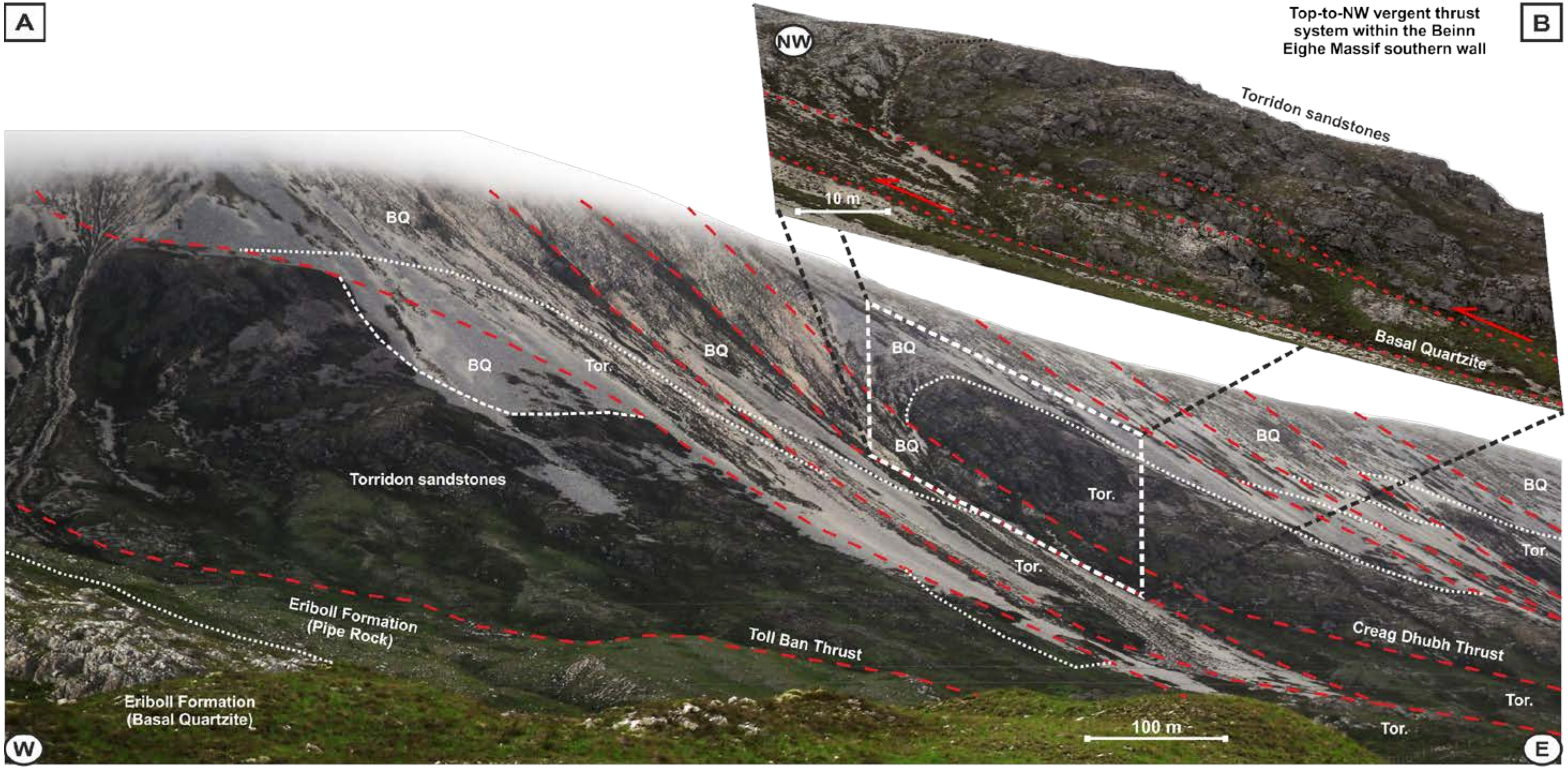


Figure 4.15: (A) Dominant thrust imbricates along the Toll Ban and Creag Dhubh thrust faults south of Sgurr nan Fhir Duibhe [NG 9872 5899]. Seven thrust splays are identified branching off the main Creag Dhubh Thrust all of which display only small amounts of displacement (10-20 m). These thrust splays are identified cutting up the Beinn Eighe southern wall, geometrically and stratigraphically, from Eriboll Formation quartzites (BQ) to Torridonian sandstones (Tor.), creating hanging-wall and footwall profiles within the fault network analyses. **(B)** Small thrust displacements along one of the seven thrust splays creating hanging-wall anticlines, identifying a top-to-NW vergent thrust system within the southern Beinn Eighe wall sequence. Thrust units show minimum internal deformation, further supporting small displacements along these thrust splays.

Formation dominant thrust imbrications [NG 9580 5961], creating a long hanging-wall ramp profile forelandward of the one kilometre Torridonian sandstone sequence within the Coire an Laoigh Thrust hanging-wall (Figure 4.12a [6]; 4.12b [4]; 4.13b [5]).

4.4.1.2. Beinn Eighe Massif northern wall: Creag Dhubh to Ruadh-stac Mòr

By comparison to the southern wall, the northern wall comprising Creag Dhubh [NG 9856 6079], Leathad Buidhe [NG 9880 6120], Au Ruadh-stac Beag [NG 9729 6137] and Ruad-stac Mòr [NG 9513 6115] (Figure 4.16a), highlights thick thrust imbricates compromising predominantly Eriboll Formation quartzites. Notable exceptions include the Coire an Laoigh and Toll Ban thrusts, which contain one hundred fifty to two hundred fifty metres of Torridonian sandstones (Figure 4.12a [7, 8]; 4.12b [1, 2]).

Whilst several major thrust sheets, such as the Sgurr na Conghair, Coire Domhain and Meallan na Circe-fraoich are laterally continuous along-strike within the Beinn Eighe Massif southern and northern walls (Figure 4.12a [3]); thrust map-traces indicate that numerous splays identified within the southern wall coalesce to form only a few dominant major thrusts (spaced hundreds of metres apart) within the northern wall (e.g., Creag Dhubh, Toll Ban and Spidean Coire nan Clach thrusts; Figure 4.12a [2, 8]; 4.12b [1, 2, 3, 5, 6]). Thrust imbricates within the fault network analysis identify more dispersed frontal hanging-wall and footwall ramps comprising longer profiles, especially within the hinterland Coire Domhain and Meallan na Circe-fraoich thrust sheets along the Allt a' Chuirn river (east of Creag Dhubh [NG 9988 6063]) and Meallan na Circe-fraoich hillside [NH 0049 6100]. Fault network analyses also identify numerous thrust-tip line terminations and / or nucleations aligned sub-parallel to regional transport within this region (Figure 4.12a [9]; 4.12b [7, 8]).

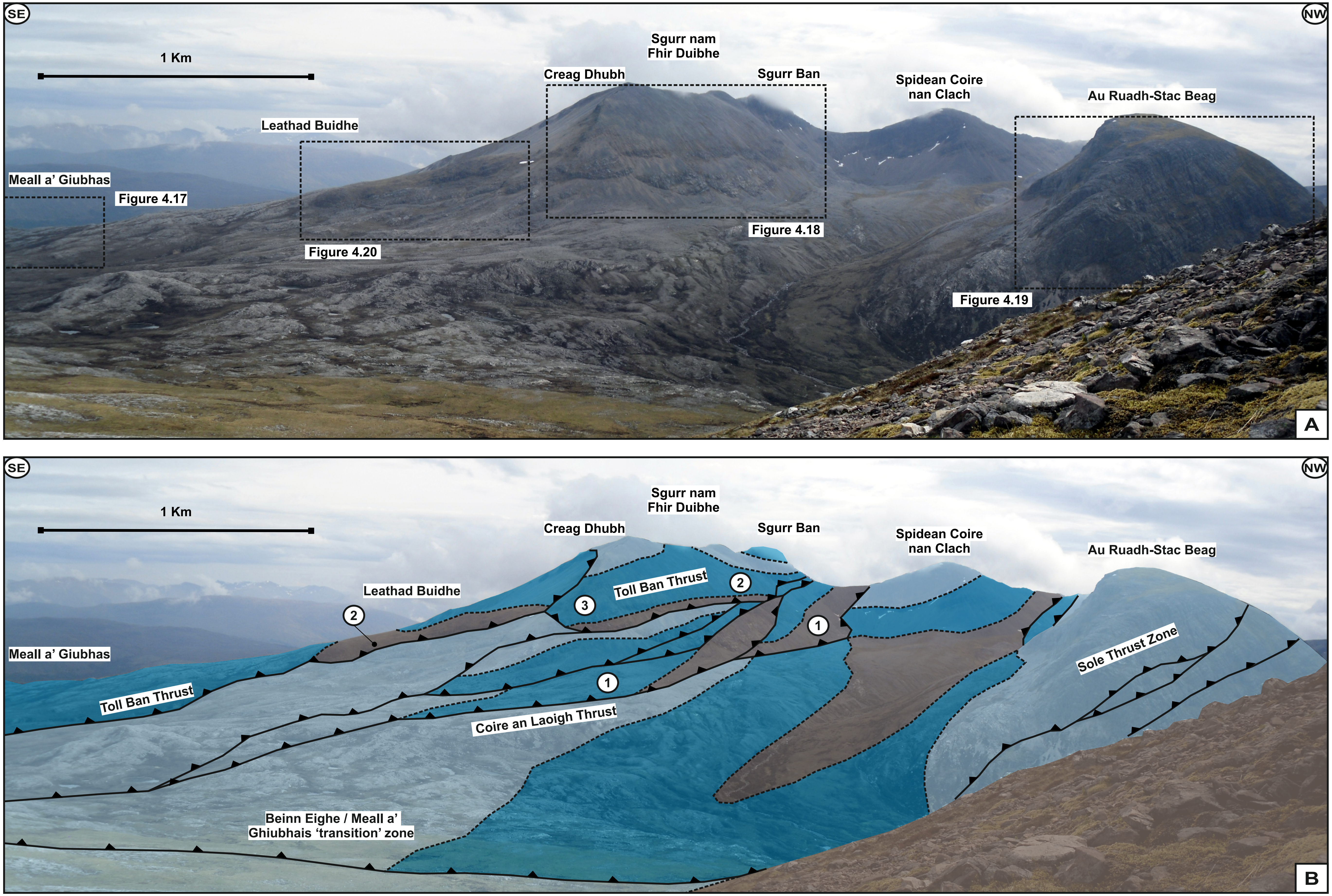


Figure 4.16: (A) Beinn Eighe Massif northern wall comprising Creag Dhubh [NG 9856 6079], Leathad Buidhe [NG 9880 6120], Au Ruadh-stac Beag [NG 9729 6137] and Ruad-stac Mòr (out of image) [NG 9513 6115]. Individual figure locations are identified and discussed within text. **(B)** Geological overlay within Beinn Eighe Massif northern wall. A distinct map-view alternation within Torridonian sandstones is observed south to north across the Beinn Eighe Massif. Within the northern wall, evidence for alternating forelandward- and hinterlandward-propagation is supported by field evidence along the Toll Ban Thrust [2, 3] and Sole Thrust Zone.

Key

BQ / Pr — **Eriboll Formation (Basal Qtz./Pipe Rock)**

Torridon Sandstones

Thrust

Along the Meallan na Circe-fraoich hillside, structural styles illustrate pre-thrust folding and thrusting interactions within the Meallan na Circe-fraoich Thrust Sheet, supporting long hanging-wall and footwall ramp profiles along-strike (Figure 4.12a [10];4.12b [8, 9]). North of Meallan na Circe-fraoich, a large pre-thrust fold is identified along the Meall a' Giubhas hillside [NH 0047 6142] (Figure 4.16a; 4.17a). Thrust imbricates within the transition zone from the Beinn Eighe Massif sector to the Meall a' Ghiubhais sector are large in nature, dominated by bulged and overturned Eriboll Formation quartzites (Figure 4.12a [10]; 4.17a). Hinterland-propagating thrusting is indicated within this section as higher thrusts truncate lower thrusts, hanging-wall anticlines and fold cores within the sequence (Figure 4.17b). Forelandward of this structure, numerous thrust bifurcations are observed within the fault network analysis within the Meallan na Circe-fraoich Thrust hanging-wall [NH 0049 6208] (Figure 4.12a [11]) and along the Sgurr na Conghair Thrust [NG 9984 6210] (Figure 4.12a [12]); suggesting a potential cross-strike sub-décollement link with structures observed within the Meallan na Circe-fraoich hillside (Figure 4.12b [8, 9]).

Within the forelandward sections of the Beinn Eighe Massif northern wall along Chreag Dhubh [NG 9856 6079] and Leathad Buidhe [NG 9880 6120], further thrust map-traces are dominated by branch-points within the fault network analyses (Figure 4.12b [5, 6, 10]). Thrust bifurcation appears prevalent within these regions as a result of large rheological or stratigraphical thickness changes along-strike, where thrust ramps can be seen to incorporate Torridonian sandstones and / or large thrust sheets of Eriboll Formation quartzites (Figure 4.16b [1, 2]).

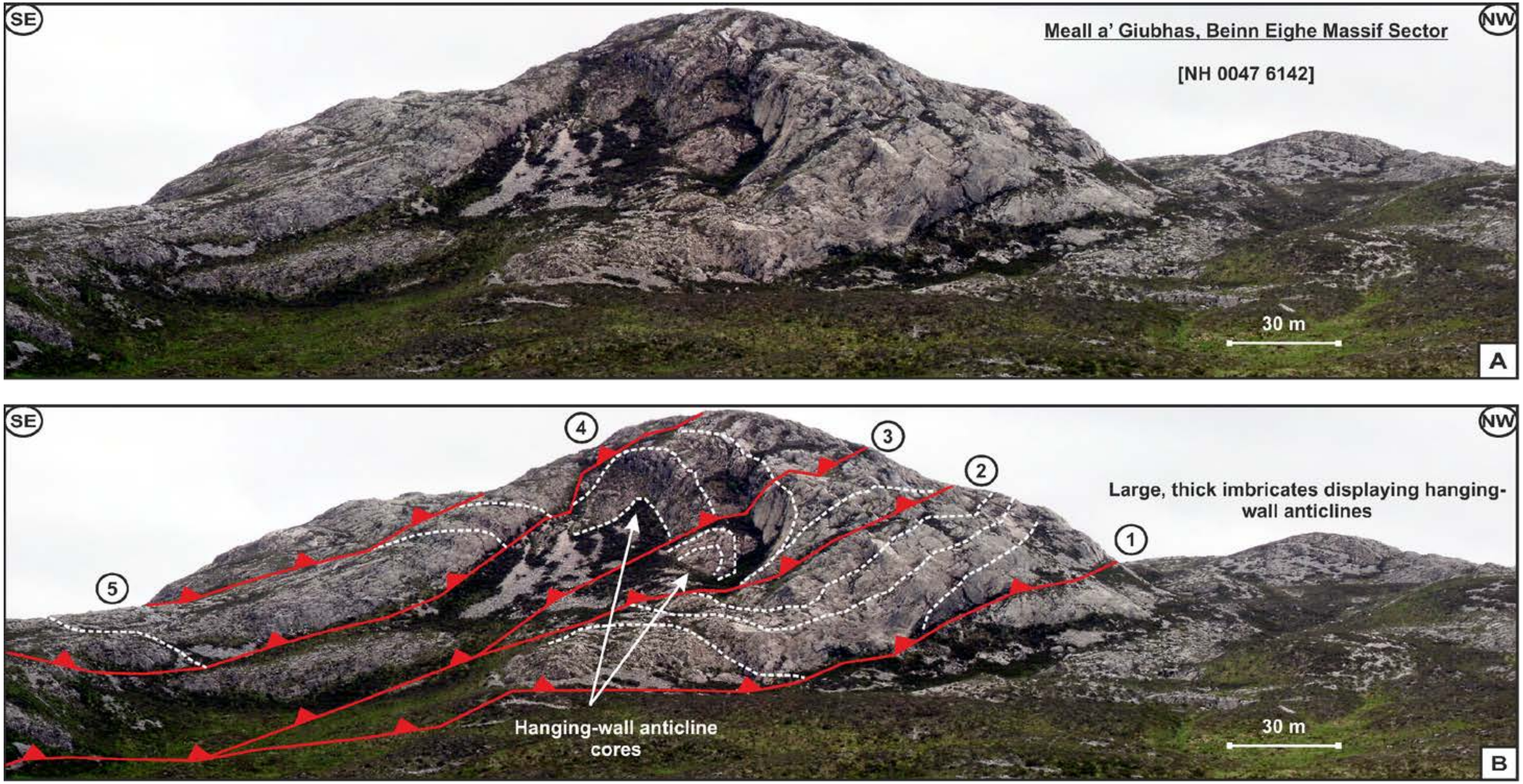


Figure 4.17: **(A)** Meall a' Giubhas hillside indicating pre-thrust folding/thrusting interactions. Units composed of bulged and locally overturned Eriboll Formation quartzites (location within Figure 4.12a [10]). **(B)** Large thrust imbricates indicating out-of-sequence (hinterland-propagating) thrust phases. Higher thrusts truncate underlying thrusts, hanging-wall anticlines and fold cores. Suggested phases of movement are numbered within this sequence, however multiply phases between foreland- and hinterland-propagating sequences are observed indicating an oscillation thrust system (e.g., thrusts [2, 3] branch off the same thrust but develop separately creating differing hanging-wall and footwall structures).

Within Creag Dhubh [NG 9856 6079] and Au Ruadh-stac Beag [NG 9729 6137] further evidence can be identified supporting phases of hinterland-propagating thrusting (Figure 4.12a [7, 8, 13]; 4.16a). Within Chreag Dhubh, higher thrust imbricates containing Torridon sandstones at their base truncate lower thrust imbricates containing Eriboll Formation quartzites (Figure 4.18). Observations suggest that the Coire an Laoigh, Toll Ban and it’s branching hanging-wall and footwall thrusts (i.e., Creag Dhubh Thrust) may all have at one phase experienced out-of-sequence (hinterland-propagating) or oscillatory (i.e., forelandward-hinterlandward-forelandward) thrust movements. Hinterland-propagating thrusting is replicated within Au Ruadh-stac Beag (Figure 4.19), where lower thrust sheets are also truncated indicating hinterland-propagation even within the Sole Thrust Zone. Large fault-propagation folding can also be seen indicating that although oscillatory thrust phases are present within the foreland portions of the Beinn Eighe Massif; regional transport (i.e., 290 / 300°) is maintained.

Further complexities are identified within the Leathad Buidhe region where a distinct kink is observed within the fault network along the Toll Ban Thrust [NG 9880 6120] (Figure 4.12a [8]; 4.12b [10]; 4.16b [3]; 4.20a), one of only a few dominant imbricates carrying Torridonian sandstones over Spidean Coire nan Clach [NG 9682 5952] and Sgurr nam Fhir Duibhe [NG 9814 6004]. Small one metre thick ‘lenses’ of Eriboll Formation (Basal Quartzite Member) are entrained within the larger Torridonian sandstone dominant thrust imbricates along hanging-wall splays (Figure 4.20b, 4.20c). Torridonian sandstones structurally above show little evidence of thrusting, indicating that deformation must have been focused within the Basal Quartzite lenses beneath.

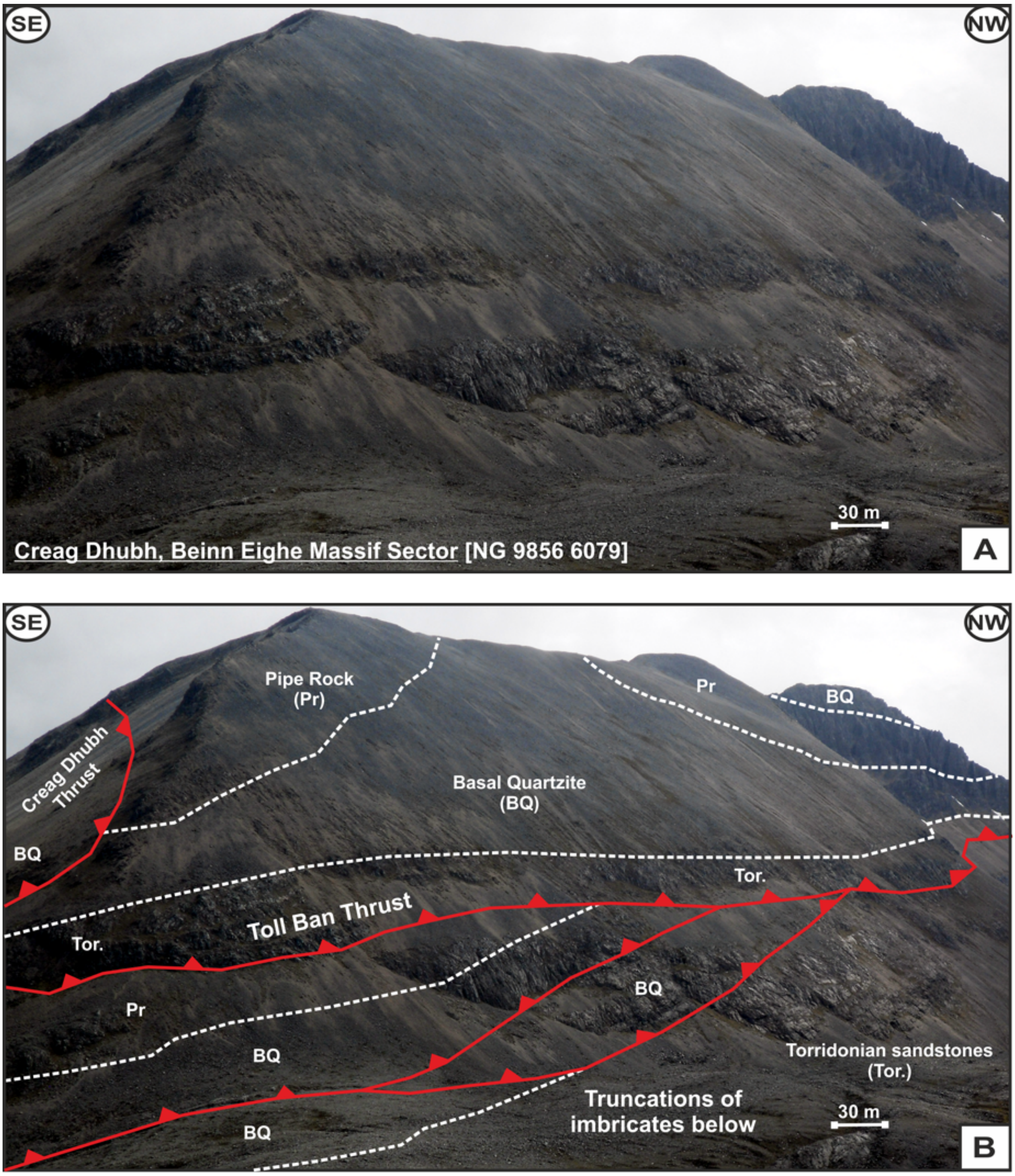


Figure 4.18: **(A)** Creag Dhubh, Beinn Eighe Massif northern wall [NG 9856 6079] highlighting areas of interest. **(B)** Structural overlay of the Creag Dhubh section highlighting truncations of lower thrust imbricates by the Toll Ban Thrust, which carries Torridonian sandstones to Eriboll Formation lithologies within its hanging-wall. This indicates at least one phase of hinterland-propagation within the Beinn Eighe Massif. Creag Dhubh also truncates the lower Toll Ban thrust placing Basal Quartzites on Pipe Rock units.

However, ten metres further towards the north, undeformed Torridonian units containing perfectly preserved trough cross-bedding (Applecross Formation; Figure 4.21 [1]) are overrun by a ten metre thick zone of heavily deformed and sheared sandstones (although not similar in nature to the Coulin sheared sandstones; Figure 4.21 [2]). Units correlate on

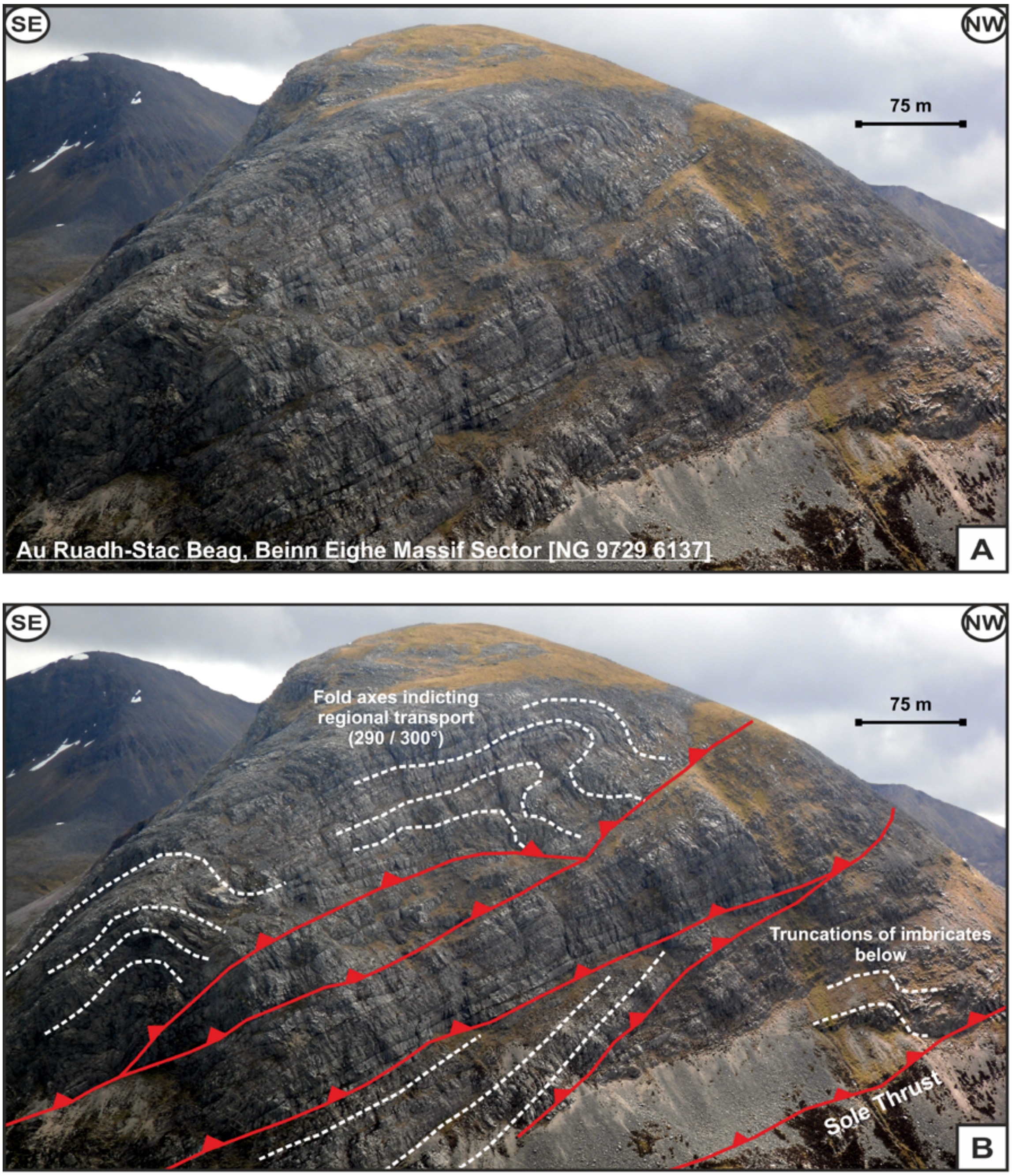


Figure 4.19: (A) Au Ruadh-stac Beag, Beinn Eighe Massif northern wall [NG 9856 6079] highlighting areas of interest within Sole Thrust Zone. **(B)** Structural overlay of Au Ruadh-stac Beag section highlighting truncations of lower thrust imbricates by higher thrusts within the Sole Thrust Zone; indicating at least one phase of hinterland-propagation as far forward as the Sole Thrust Zone. Fold axes also indicate that whilst oscillatory thrusting between forelandward- and hinterlandward-propagating thrusts are observed, regional transport is still maintained (i.e., 290 / 300°).

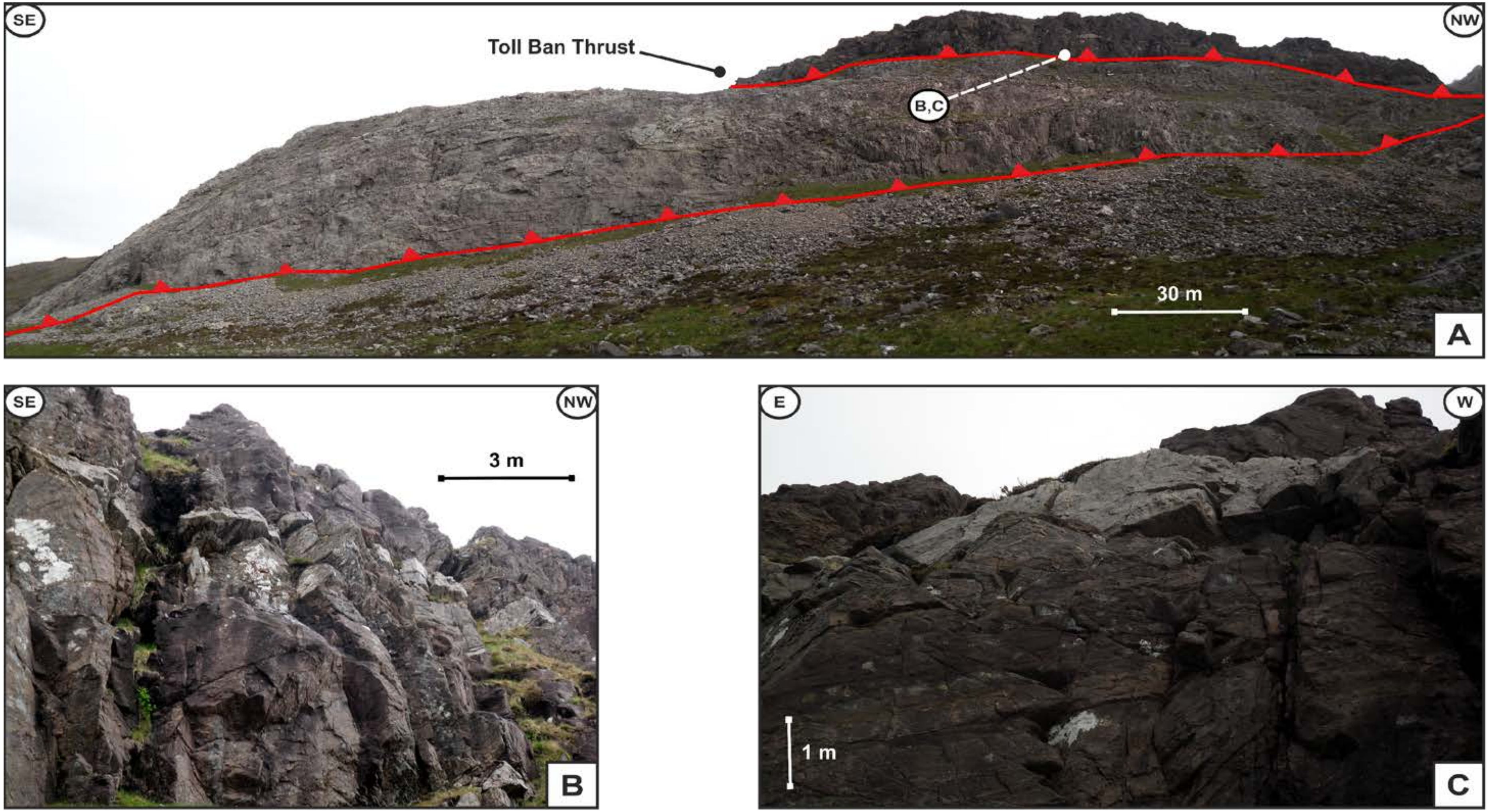


Figure 4.20: (A) Leathad Buidhe region where a distinct kink is observed along the Toll Ban Thrust placing Torridonian sandstones on top of Eriboll Formation (Pipe Rock member) units [NG 9880 6120] indicating deformation associated with buttressing. **(B, C)** One metre thick Eriboll Formation (Basal Quartzite) lenses which appear internally undeformed. Unconformity between Torridonian sandstones and Eriboll Formation established. Observations support hinterland-propagation along the Toll Ban Thrust down-cutting into the underlying Eriboll Formation (Basal Quartzites).

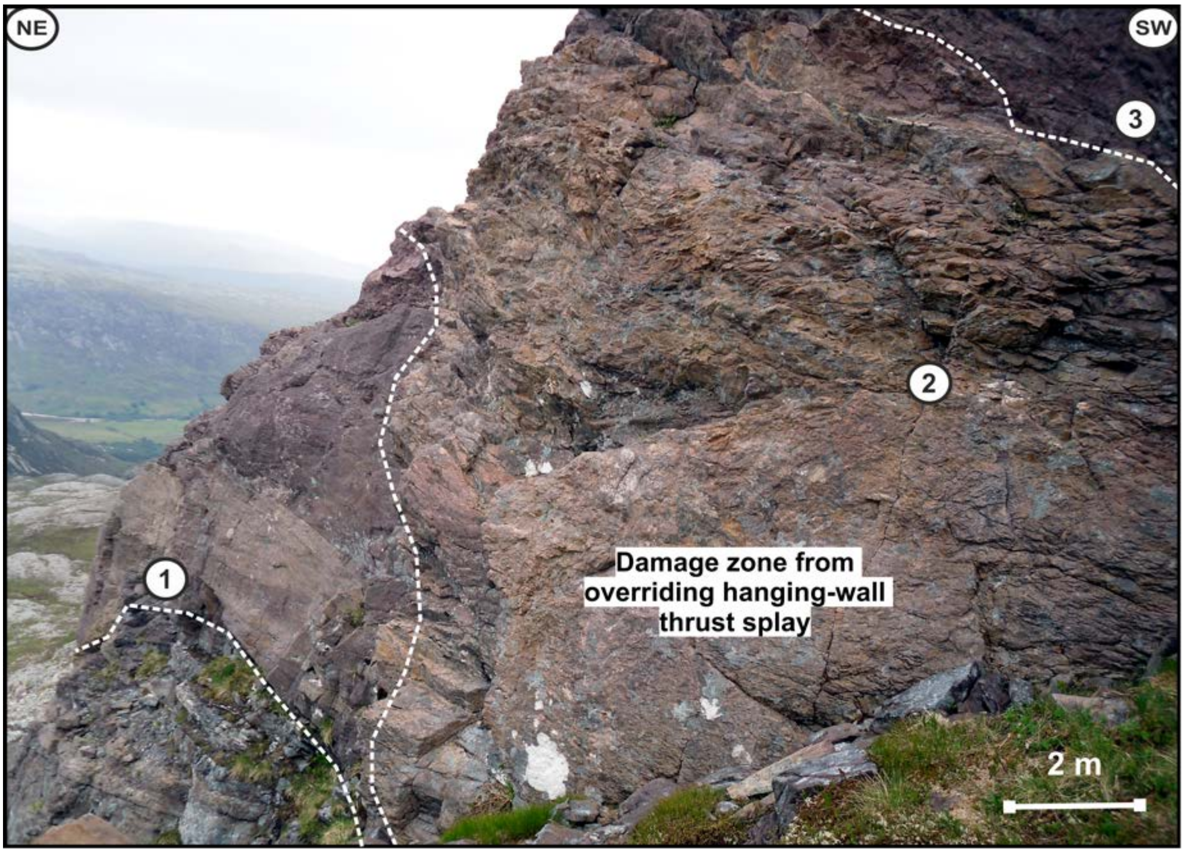


Figure 4.21: Units within the Leathad Buidhe section along the Toll Ban Thrust [NG 9880 6120]. Toll Ban Thrust at base of undeformed Torridonian sandstones containing perfectly preserved cross-bedded channels (Applecross Formation **[1]**) are overridden by a 10 m thick zone of heavily deformed and sheared sandstones **[2]** within the footwall of a hanging-wall thrust splay of the Toll Ban Thrust, indicating a hinterlandward-propagating phase of thrust movement. Undeformed Torridonian sandstones then return **[3]**.

a similar topographic level as the Eriboll Formation (Basal Quartzite) lenses; indicating deformation within the footwall of the thrust structurally above (i.e., a Toll Ban hanging-wall splay), further supporting hinterland-propagation. This thrust creates a distinct two metre shelf above which undeformed Torridonian sandstones return (Figure 4.21 [3]).

The underlying Toll Ban Thrust carries these hanging-wall Torridonian sandstones onto Eriboll Formation (Pipe Rock Member) units, indicating a dominant thrust with large along-strike stratigraphical separation. The Toll Ban within this region also truncates its footwall cutting off the tops of folded Eriboll Formation units beneath [NG 9799 6056], further supporting an out-of-sequence aspect to the Toll Ban Thrust. Observations lie sub-parallel to map-view branch-points and fault-tip points within the fault network analysis, suggesting a forelandward continuation of a potential sub-décollement structure from Meallan na Circe-fraoich and Meall a' Giubhas [NH 0049 6100] (Figure 4.12a [9, 10, 11, 12]; 4.12b [7, 8, 9]) towards Leathad Buidhe [NG 9880 6120] (Figure 4.12a [8]; 4.12b [10]). This deformation zone is forthwith termed the 'transition zone' between the Beinn Eighe Massif and Meall a' Ghiubhais sector.

Within the forelandward transition zone between the Beinn Eighe Massif northern wall and the Meall a' Ghiubhais sector, Eriboll Formation quartzites comprise the only lithologies within map-view. Imbricate styles within the 'transition zone' are laterally variable, from heavily fractured units within the footwall of the Toll Ban Thrust along Leathad Buidhe [NG 9799 6056] (Figure 4.22a) to near vertical units towards the Meall a' Ghiubhais sector [NG 9877 6193] (Figure 4.22b). Eriboll Formation quartzites within the Leathad Buidhe region are also heavily fractured as a result of later glacial and freeze-thaw elements creating a prominent boulder-field.

Transition zone imbricates display little internal deformation, evidenced by undeformed *Skolithos* burrows within Eriboll Formation (Pipe Rock Member) units (Figure 4.22c). This suggests that deformation is accommodated by layer-parallel shortening between bedding planes; supporting observations by Butler *et al.,* (2007) (Figure 4.22d). Along-strike changes within the 'transition zone' may be as a result of differential shortening, greater slip within this region, or potential along-strike sub-surface obstacles causing buttressing along-strike. All these elements may play a part, however, units observed also lie within the Coire an Laoigh Thrust hanging-wall, which is observed cutting-up stratigraphically from Torridonian sandstones to Eriboll Formation (Pipe Rock Member) units (Figure 4.12a [14]; 4.12b [11]). This may also account for along-strike differential deformation.

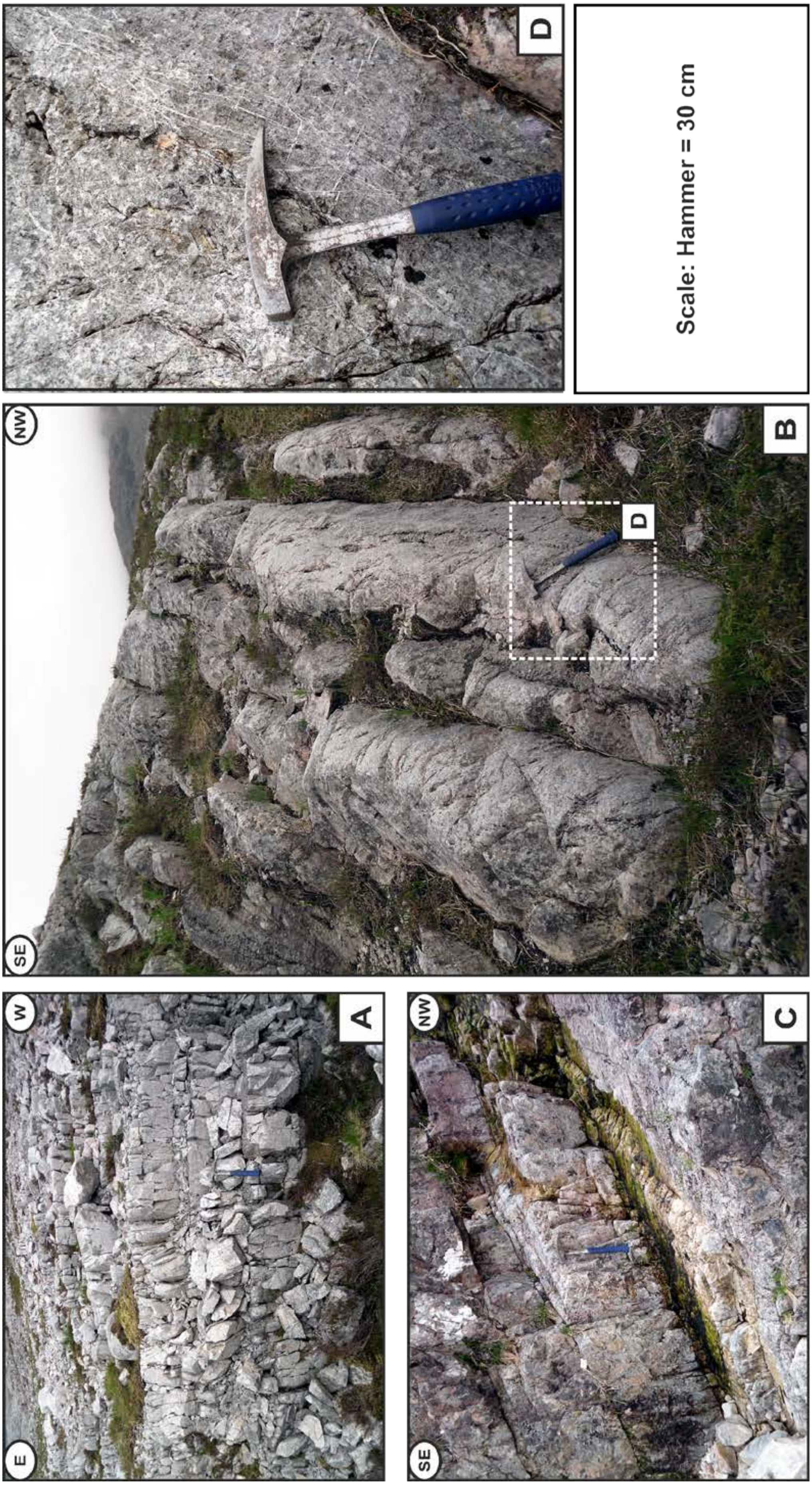


Figure 4.22: **(A)** Heavily fractured Eriboll Formation quartzites within the Leathad Buidhe region. **(B)** Eriboll Formation (Pipe Rock member) units indicating vertical to overturned units within the Beinn Eighe Massif/Meall a' Ghiubhais 'transition zone'. **(C)** Eriboll Formation quartzites depicting later-parallel shearing between bedding planes. Imbricates also show little internal deformation of the *Skolithos* 'pipes' **(D)** supporting layer-parallel shear observations by Butler *et al.*, (2007).

4.4.1.3. Beinn Eighe Massif Sector: Cross-strike three-dimensional distribution

Map patterns identified within Figure 4.12a; 4.13b; 4.16b and field observations described within previous sections clearly identify a series of cross-strike discontinuities across the Beinn Eighe Massif from the hinterland Meallan na Circe-fraoich Thrust Sheet to the Sole Thrust Zone. Cross-strike map patterns and cross-sections (located on Figure 4.1; 4.12a), indicate a north-south trending cross-strike discontinuity creating a significant and sudden drop southwards in detachment level, resulting in a rapid increase of Torridonian sandstones entrained within thrust imbricates. A further structural discontinuity is identified orientated sub-parallel to the Beinn Eighe Massif (i.e., east-west) creating a structural change in thrust architecture along regionally dominant thrusts, such as the Toll Ban Thrust, supporting the findings of Cain (2013).

South to north across the Beinn Eighe Massif, Cain (2013) identified through cross-sectional analysis and field observations, a distinct change of Torridonian thickness from thrusts containing up to one and a half kilometres of Torridonian sandstones within the southern wall (Figure 4.23a [1]); compared to imbricates within the northern wall containing up to six hundred metres within hinterland sections of the northern wall (Figure 4.23b [1]). Observations within this research support observations by Cain (2013) within the southern wall of the Beinn Eighe Massif in which one and a half kilometres of Torridonian sandstones are entrained within thrust imbricates, raising to two kilometres further south within the Achnashellach Culmination, supporting observations by Butler *et al.,* (2007). However, across the Beinn Eighe Massif, no evidence for up to six hundred metres of Torridonian sandstones is visible within map-view. This research proposes only up to three hundred metres based on field observations within Leathad Buidhe along the Toll Ban Thrust (Figure 4.24a [1]) and Coire an Laoigh Thrust (Figure 4.24a [2]), containing between one hundred fifty and three hundred metres and its continuation

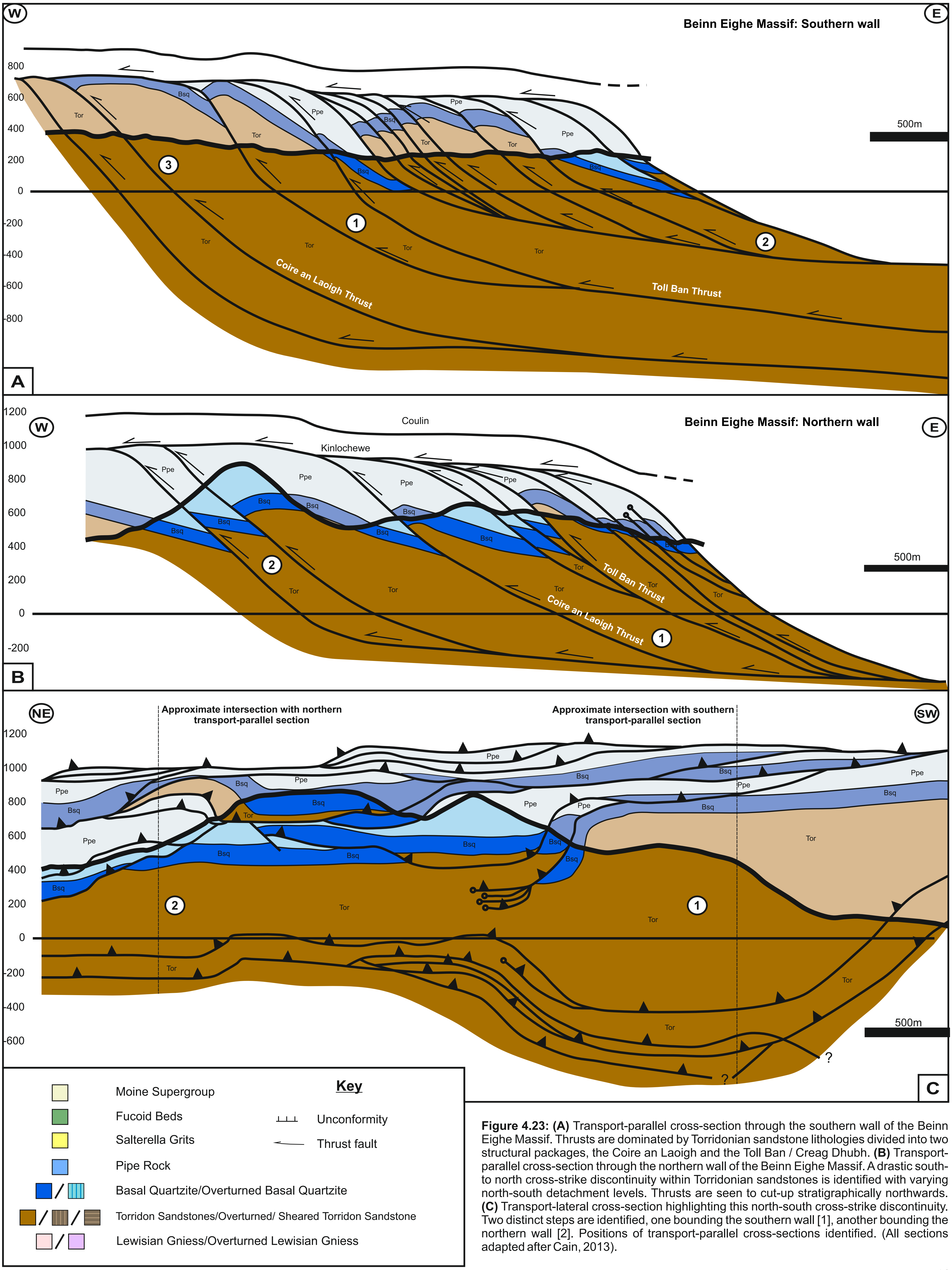


Figure 4.23: (A) Transport-parallel cross-section through the southern wall of the Beinn Eighe Massif. Thrusts are dominated by Torridonian sandstone lithologies divided into two structural packages, the Coire an Laoigh and the Toll Ban / Creag Dhubh. **(B)** Transport-parallel cross-section through the northern wall of the Beinn Eighe Massif. A drastic south-to north cross-strike discontinuity within Torridonian sandstones is identified with varying north-south detachment levels. Thrusts are seen to cut-up stratigraphically northwards. **(C)** Transport-lateral cross-section highlighting this north-south cross-strike discontinuity. Two distinct steps are identified, one bounding the southern wall [1], another bounding the northern wall [2]. Positions of transport-parallel cross-sections identified. (All sections adapted after Cain, 2013).

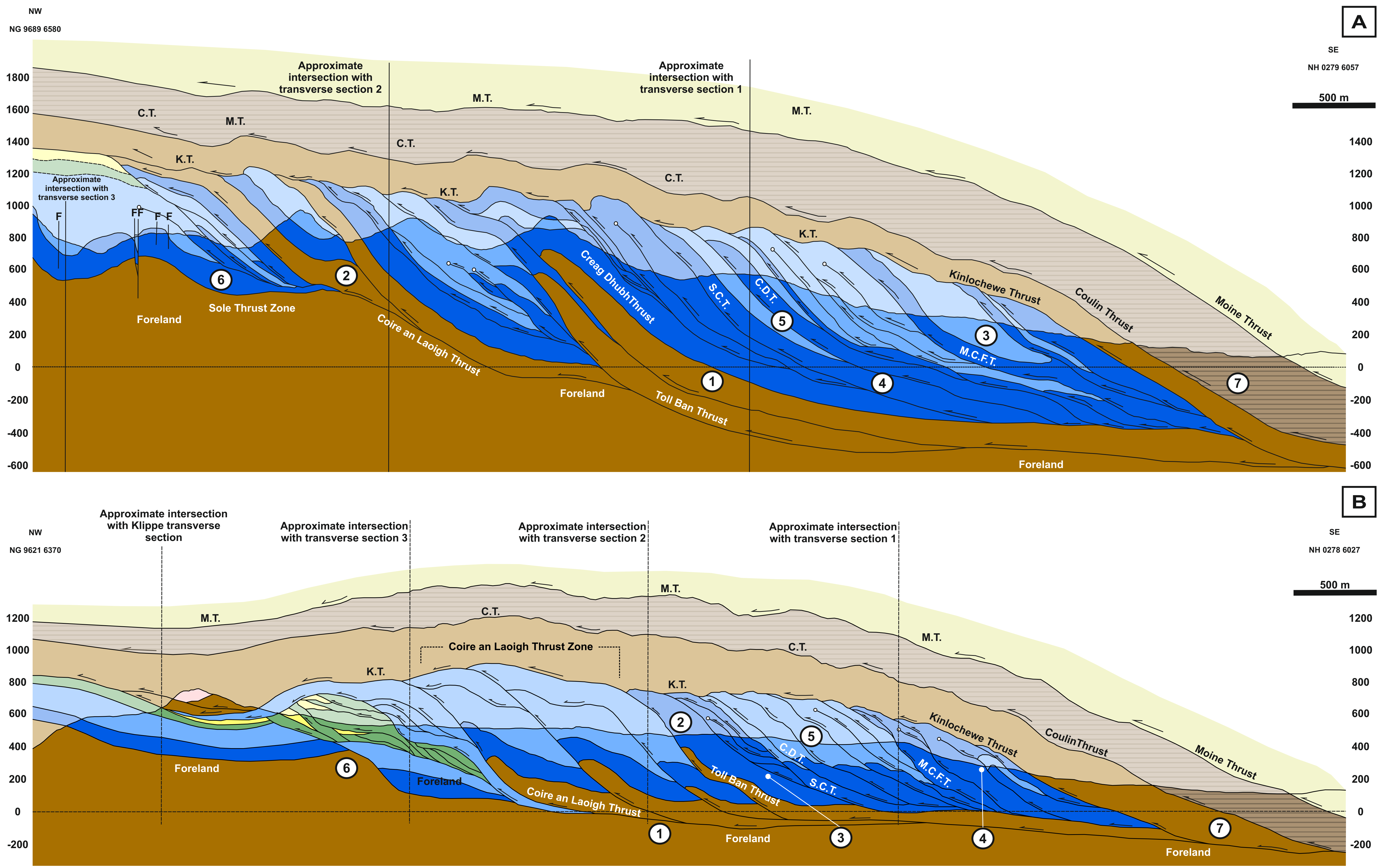


Figure 4.24: (A) Transport-parallel cross-section of the Beinn Eighe Massif, comprising a 1.2 km package of Torridonian sandstone and Eriboll Formation quartzites (B) Transport-parallel cross-section of the Beinn Eighe Massif/Meall a' Ghuibhais 'transition zone', comprising a 800 m package dominated by Eriboll Formation quartzites, highlighting the north-south cross-strike discontinuity. Individual observations identified within text are numbered within both section lines, whilst approximate positions of intersecting transport-lateral cross-sections are also identified. Cross-section locations placed within Figure 4.1 and Figure 4.12a. (S.C.T = Sgurr na Conghair Thrust; C.D.T. = Coire Domhain Thrust; M.C.F.T. = Meallan na Circe-fraoich Thrust).

Key

- Basal Quartzite/Overturned Basal Quartzite
- Torridon Sandstones/Overturned/ Sheared Torridon Sandstone
- Lewisian Gneiss/Overturned Lewisian Gneiss
- Moine Supergroup
- Fucoid Beds
- Salterella Grits
- Pipe Rock
- Unconformity
- Thrust fault

northwards towards the Beinn Eighe Massif / Meall a' Ghiubhais transition zone where only one hundred to two hundred metres of Torridonian sandstone are identified (Figure 4.24b [1]).

A transport-perpendicular cross-section constructed by Cain (2013) (Figure 4.23c) identified two potential steps within the detachment level along-strike. The first bounding the Beinn Eighe southern wall, proposed by Cain (2013) to be the edge of a large pre-thrust Torridonian sandstone horst block which experienced post-depositional movement, placing Torridonian sandstones at a level for thrust propagation (i.e., Beinn Eighe lateral ramp); observations supported within this research (Figure 4.23c [1]). A second step identified within the northern wall orientated sub-parallel to regional transport along Leathad Buidhe [NG 9799 6056] was also suggested (Figure 4.23c [2]).

Observations for this second step, termed here the Leathad Buidhe Transverse Structure (LBTS), are supported within this research as fault network and field observations indicate a sub-surface transverse structure running slightly oblique / sub-parallel to regional transport (i.e., 280°) from the Meallan na Circe-fraoich and Meall a' Giubhas hillsides [NH 0049 6100 and 0047 6142], where map-view thrust-tip lines indicate a thrust nucleation / termination zone, pre-thrust folding and out-of-sequence thrusting (Figure 4.12a [9, 10]; 4.17; 4.24a [3, 4]); forelandward towards Leathad Buidhe [NG 9880 6120], where numerous thrust branches occur within the hanging-walls of the Meallan na Circe-fraoich, Coire Domhain, Sgurr na Conghair and Toll Ban thrusts (Figure 4.12a [8, 11, 12]; 4.24b [3]).

Cross-section analyses also identify several discontinuities sub-parallel to the Beinn Eighe Massif (Figure 4.1; 4.12a). Within the hinterland sections of the Beinn Eighe Massif, Cain (2013) suggested that thrust imbricates within the Toll Ban / Creag Dhubh structural package, comprising three hundred metres repetitions of Torridonian sandstones, were confined to a higher structural décollement than those within the underlying Toll Ban Thrust (Figure 4.23a [1, 2]). This observation is supported within this research, as along-strike this higher décollement comprises solely Eriboll Formation quartzites within the Creag Dhubh, Sgurr na Conghair, Coire Domhain and Meallan na Circe-fraoich thrusts (Figure 4.24a [4]), suggesting a thrust décollement along the Torridonian sandstone and Eriboll Formation unconformity interface across the Beinn Eighe ridge.

Thrust sheets within the hanging-wall of these thrusts, which indicate phases of oscillatory thrusting between forelandward- and hinterlandward-propagation (Figure 4.24a [3, 4, 5]), are laterally continuous into the Beinn Eighe Massif / Meall a' Ghiubhais 'transition zone' and beyond (Figure 4.24b [3, 4, 5]); with the notable exception of the Creag Dhubh Thrust which branches off the Toll Ban Thrust and continues into the Meall a' Ghiubhais sector (Figure 4.12a [12]; 4.24b [2]). This bifurcation coincides with branching along the Sgurr na Conghair Thrust and is suggested to be a response to the underlying Leathad Buidhe Transverse Structure (LBTS).

The Toll Ban Thrust acts as a regionally dominant thrust from the Meall a' Ghiubhais sector southwards into the Beinn Eighe Massif separating the 'thin flap' Toll Ban / Creag Dhubh structural imbricates from the 'thick slab' Coire an Laoigh structural package within a lower thrust décollement level (Figure 4.12a [1, 2]; 4.24a [1]; 4.24b [2]). Field observations and cross-sections identify the Toll Ban Thrust Sheet as being dominated by thick thrust sheets composed of Torridonian sandstones and Eriboll Formation (Basal

Quartzites), supporting the observations of Cain (2013) (Figure 4.15; 4.24a [1]). Along-strike, the Toll Ban Thrust highlights numerous map-view thrust branches within its footwall (e.g., Spidean Coire nan Clach [NG 9682 5952]; Figure 4.12a [5]) and hanging-wall (e.g., Creag Dhubh Thrust splay system [NG 9879 5949]; Figure 4.12a [4]) which indicate out-of-sequence thrusting along-strike (e.g., Creag Dhubh / Leathad Buidhe hillside; Figure 4.18; 4.19).

Forelandward of the Toll Ban Thrust, the Coire an Laoigh Thrust (Figure 4.24a [2]) drastically cuts-up stratigraphically northwards from one kilometre Torridonian sandstones within its hanging-wall within the Beinn Eighe Massif southern wall, to three hundred metres within the Beinn Eighe northern wall and one hundred to two hundred metres within the Beinn Eighe Massif / Meall a' Ghiubhais 'transition zone' where it branches into the Coire an Laoigh / Toll Ban Thrust system (Figure 4.23a [3]; 4.24a [2]; 4.24b [1]). Thrust sheets within the Coire an Laoigh hanging-wall rapidly thicken northwards towards the Meall a' Ghiubhais sector, containing up to two hundred metres of Eriboll Formation quartzites (Figure 4.24b [1]).

Within the Còinneach Mòr region, the Sole Thrust Zone is observed drastically cutting-up stratigraphically from Torridonian sandstones to Eriboll Formation quartzites within a defuse zone of thrusts within the Còinneach Mòr hillside (Figure 4.12a [6]). Thrust architectures indicate a series of shortcut thrusts off the main Sole Thrust composing this zone of deformation (Figure 4.24a [6]). Development of this defuse zone is considered to be a response to thrust propagation cutting upwards within the regional transport direction (i.e., 290 / 300°) through the pre-thrust Torridonian sandstone horst block identified within Cain (2013), before reaching Eriboll Formation quartzites. At this stratigraphical level thrust propagation rapidly increases due to the more thinly bedded nature of the quartzites, creating the defuse zone. Along-strike the Sole Thrust Zone develops from this defuse zone into two dominant thrusts identified within Au Ruadh-stac Beag (Figure 4.12a [13]; 4.19; 4.23b [2]). Thrusts observed within Au Ruadh-stac Beag are identified to have out-of-sequence elements suggesting oscillatory thrusting ranging from the Toll Ban Thrust to the Sole Thrust Zone (Figure 4.19).

Within the Beinn Eighe Massif / Meall a' Ghiubhais 'transition zone', a defuse zone of thrust imbricates within the hinterland of the Meall a' Ghiubhais Klippe are identified with the Sole Thrust at the base of the Klippe (Figure 4.24b [6]). This region is explained in greater detail within the following Meall a' Ghiubhais Sector. Overall, the transition from the Beinn Eighe Massif northwards towards the Meall a' Ghiubhais sector and the Loch Maree Fault indicate a thinning of the footwall imbricate package from 1.2 kilometres (Beinn Eighe) to eight hundred metres, further supporting observations of a series of cross-strike discontinuities to accommodate this along-strike variation (Figure 4.24a; 4.24b). The Kinlochewe Thrust, which acts as the roof to the footwall imbricates which dominate the Beinn Eighe Massif, laterally thickens northwards, whilst the overriding Coulin Thrust dramatically thins northwards towards the Loch Maree Fault (Figure 4.24a [7]; 4.24b [7]). This suggests that the Coulin Thrust Sheet cuts laterally downwards from north to south truncating the Kinlochewe Thrust Sheet along-strike; indicating a later out-of-sequence movement along the Coulin Thrust.

4.4.1.4. Beinn Eighe Massif Sector: Summary

Within the Beinn Eighe Massif Sector, fault network analyses and field observations allow the following pertinent characteristics to be identified within Table 4.1:

Beinn Eighe Massif Sector: Summary findings
• Regional thrust transport direction (290 / 300°) verified within the Moine, Coulin and Kinlochewe thrust sheets. Units depict lateral shortening over various scales.
• Coulin Thrust Sheet characterised by sheared Torridonian sandstones and elements of sheared gneisses. Sheath folds identified within thrust sheet.
• Kinlochewe Thrust Sheet comprises undeformed right-way-up Torridonian sandstone units, predominantly of Applecross Formation; is laterally cut out southwards by overlying Coulin Thrust Sheet. Outcrop widths of Torridonian Applecross within Beinn Eighe Massif sector reach 120-180 m compared to 1.26 km within Meall a' Ghiubhais sector.
• Kinlochewe Thrust footwall imbricates comprise Torridonian sandstones and Eriboll Formation quartzites defining a moderate to steep SE-dipping imbricate stack. Kinlochewe Thrust acts as the roof thrust to this system. Thrusts decrease in number towards the foreland.

Table 4.1: Summary findings of the Beinn Eighe Massif

Beinn Eighe Massif Sector: Summary findings	
Region	**Observation highlights**
Beinn Eighe Massif: Southern Wall	• Two distinct structural packages of right-way-up Torridonian sandstones and Eriboll Foramtion quartzites identified separated by the Toll Ban Thrust: (1) Coire an Laoigh: 1 km of 'slab-like' Torridonian sandstones within the hanging-wall of the Coire an Laoigh Thrust (interpreted as a pre-thrust, Torridonian sandstone dominant, horst block). Lithologies within foreland (10-22°) (2) Toll Ban / Creag Dhubh: repetitions of thinner (300 m) 'flap-like' Torridonian sandstone to Eriboll Formation imbricates. Back-steepening along thrusts creates steep dips (40-55°) • Tightly clustered ramp-on-ramp geometries orientated sub-parallel to regional transport direction (i.e., 290 / 300°) observed stratigraphically cutting-up from Torridonian sandstones to Eriboll Formation quartzites rapidly along a series of thrust splays within the Creag Dhubh Thrust hanging-wall. • Thrusts coalesce northwards across the Beinn Eighe ridge into only a few dominant thrusts (i.e., Toll Ban Thrust). Notable exceptions include Sgurr na Conghair and Coire Domhain thrusts which are laterally continuous south to north within the Beinn Eighe Massif hinterland. Thrust populations decrease forelandwards. • Sole Thrust within Còinneach Mòr comprises a diffuse zone of Eriboll Formation dominant thrust imbricates. Interpreted as a series of shortcut thrusts, resulting from differential thrusting after propagation through Coire an Laoigh pre-thurst Torridonian sandstone horst block.
Beinn Eighe Massif: Northern Wall	• Southern wall splays coalesce to form only a few dominant thrusts (i.e., Creag Dhubh, Toll Ban) comprising predominantly Eriboll Formation quartzites with minimal 150-300 m Torridonian sandstones, supporting observations of a major north-south cross-strike discontinuity within Torridonian sandstones (1.2 km to 300 m). Bifurcation prevalent where large rheological or stratigraphical thickness changes occur. Hinterland thrust sheets comprise solely Eriboll Formation quartzites along a higher detachment (i.e., Torridon / Eriboll unconformity interface). • Major thursts including the Meallan na Circe-fraoich, Coire Domhain, Sgurr na Conghair, Toll Ban and Sole Thrust Zone indicate out-of-sequence or oscillatory thrusting (i.e., forelandward-hinterlandward-forelandward), evidenced within Meallan na Circe-fraoich, Meall a' Ghiubhas, Creag Dhubh, Leathad Buidhe and Au Ruadh-stac Beag. • Transition zone characterised by along-strike structural variability in imbricate styles dominated by Eriboll Formation quartzites. Layer-parallel shear and layer-parallel shortening dominant as little internal deformation within imbricates (i.e., undeformed *Skolithos* burrows) • Series of pre-thrust folding, out-of sequence thrusting, numerous thrust bifurcations, terminations and nucleations along Meallan na Circe-froaich and Meall a' Giubhas hillside forlandward towards Leathad Buidhe identify sub-decollement transverse structure orientated sub-parallel to regional transport (i.e., 280°), termed here the Leathad Buidhe Transverse Structure (LBTS).
Beinn Eighe Massif: Cross-strike discontinuities	• Two senses of cross-strike discontinuity observed: (1) North-south: Drastic northwards Torridonian sandstone reduction from 1.5 km to 100-200 m within Beinn Eighe Massif. Two transverse structures observed, one along Beinn Eighe ridge (i.e., Beinn Eighe lateral ramp; Cain, 2013), second along Leathad Buidhe (Leathad Buidhe Transverse Structure [LBTS]). (2) East-west: Lateral change in thrust geometry from thick Eriboll Formation dominant thrust sheets (Coire Domhain / Sgurr na Conghair) forelandward to thin flap-like Torridon / Eriboll Formation imbricates (Toll Ban / Creag Bhubh). Develop forlandward to thick 'slab-like' Torridonian sandstone dominant region (Coire an Laoigh) into defuse Sole Thurst Zone.

Table 4.1...cont: Summary findings within the Beinn Eighe Massif. Observation highlights within southern and northern walls, whilst cross-strike discontinuities also identified.

4.4.2. Meall a' Ghiubhais Sector

The Meall a' Ghiubhais sector is dominated by the Loch Maree Fault southern wall, encompassing the Cadh' a' Mheanbh-chruidh and Carraig Alltan Mhic Eoghainn cliff line (Figure 4.25a; 4.26a [1, 2]). Similar to the Beinn Eighe Massif sector, this cliff line comprises predominantly Eriboll Formation imbricates within the Kinlochewe Thrust footwall, which carries undeformed Torridonian units within its hanging-wall and acts as the roof-thrust to the sequence (Figure 4.25a; 4.26b).

Eriboll Formation quartzite dominant imbricates within the Meall a' Ghiubhais sector are divided into two distinct structural domains identified by fault network analyses and supported by detailed field observations including, differing structural styles and thrust spacing. Boundary thrust map-traces for these different domains can be identified at:

- <u>Cadh' a' Mheanbh-chruidh domain</u>: Sole Thrust climbs the Cadh' a' Mheanbh-chruidh cliff line [NH 0071 6377] to the most forelandward thrust of the domain (i.e., Toll Ban Thrust [NH 0065 6375]; Figure 4.25a [1]; 4.26b [1]). Toll Ban Thrust stretches from the Cadh' a' Mheanbh-chruidh cliff line [NH 0038 6383] southwest to where a pod of Fucoid Bed Member outcrops [NG 9948 6283] (Figure 4.25a [2]). Toll Ban Thrust subsequently veers south-south-east into the Meall a' Ghiubhais / Beinn Eighe transition zone before entraining Torridonian sandstones within thrust imbricates at Leathad Buidhe [NG 9880 6120] (Figure 4.25a [3]).

- <u>Carraig Alltan Mhic Eoghainn domain</u>: Continues from the forelandmost thrust of the Cadh' a' Mheanbh-chruidh domain, northwest up the Carraig Alltan Mhic Eoghainn cliff line along the Sole Thrust to the forelandmost point of the thrust system (Figure 4.26a [2]); comprising An t-Sron Formation (Fucoid Bed Member) imbricates south of the Allt na h-Alrighe / Cnoc na Gaoithe fault system within the foreland [NG 9916 6432] (Figure 4.25a [4]; 4.26b [2]). Carraig Alltan Mhic Eoghainn domain continues southwest along the base of the Meall a' Ghiubhais Klippe to An t-Sron Formation (Fucoid Bed Member) imbricates at Creagan Ruadh [NG 9807 6266] (i.e., Sole Thrust transition zone; Figure 4.25a [5]). Sole Thrust re-joins at Drochaid Allt Toll a' Ghiubhais [NG 9818 6238] and continues into the Beinn Eighe Massif sector beneath Au Ruadh-stac Beag [NG 9729 6137] (Figure 4.25a [6]).

The most forelandward domain within the Meall a' Ghiubhais sector is dominated by the Meall a' Ghiubhais Klippe (eight hundred and seventy eight metres); a conical rocky hill with a summit edifice comprising two hundred fifty metres of Torridonian sandstone. This represents a tectonic outlier (klippe) of the Kinlochewe Thrust Sheet, resting upon a plinth of Cambrian foreland strata (Figure 4.25a [7]; 4.26a [3]; 4.26b [3]; Butler *et al.,* 2007). New 1:10,000-scale mapping places the Sole Thrust below the Meall a' Ghiubhais Klippe in agreement with previous interpretations (i.e., Peach *et al.,* 1907; Matthews, 1984; Butler *et al.,* 2006; 2007). However, in comparison to these interpretations, which suggested that thrust map-traces continue from the Meall a' Ghiubhais Klippe into Loch Maree perpendicular to the Carraig Alltan Mhic Eoghainn / Cadh' a' Mheanbh-chruidh cliff-line; detailed analysis identifies the Sole Thrust cutting down the cliff-line [NH 00020 6417] at the base of the two aforementioned domains (Figure 4.25a [1, 4]). These observations greatly alter the developmental interpretation of this sector, identifying a series of transport-parallel and transport-lateral cross-strike discontinuities within the core of the Loch Maree Transverse Zone.

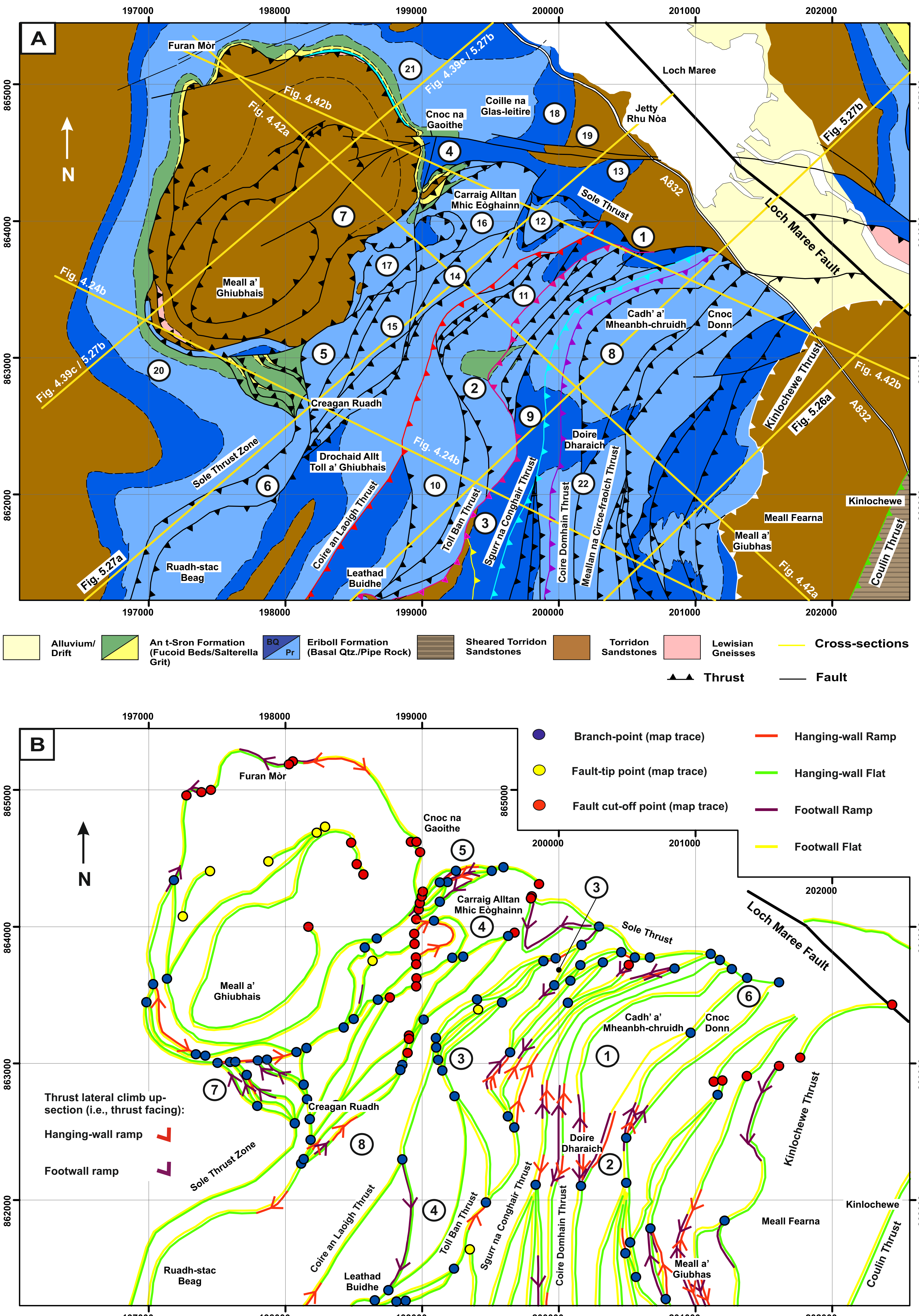


Figure 4.25: (A) Geological map of the Meall a' Ghiubhais sector, identifying a series of transport-lateral and transport-parallel discontinuities. A northeast-southwest structural style change is identified along the Toll Ban / Coire an Laoigh thrust system from a series of thick 'slab-like' 400 m structural packages within the Beinn Eighe / Meall a' Ghiubhais transition zone, to a 200 m 'flap-like' geometry along the Cadh' a' Mheanbh-chruidh / Carraig Alltan Mhic Eoghainn cliff line. Sole Thrust identified along the base of this cliff line sequence. Distinct structural change also identified within the transport direction between the Cadh' a' Mheanbh-chruidh and Meall a' Ghiubhais domains. Observations highlighted within the text are numbered. **(B)** Fault network analysis of the Meall a' Ghiubhais sector. Distinct alignments of thrust ramps and thrust bifurcations within the Doire Dharaich region are identified highlighting a potential sub-decollement structure. Forelandward continuations of this structure are also suggested. Observations highlighted within the text are numbered.

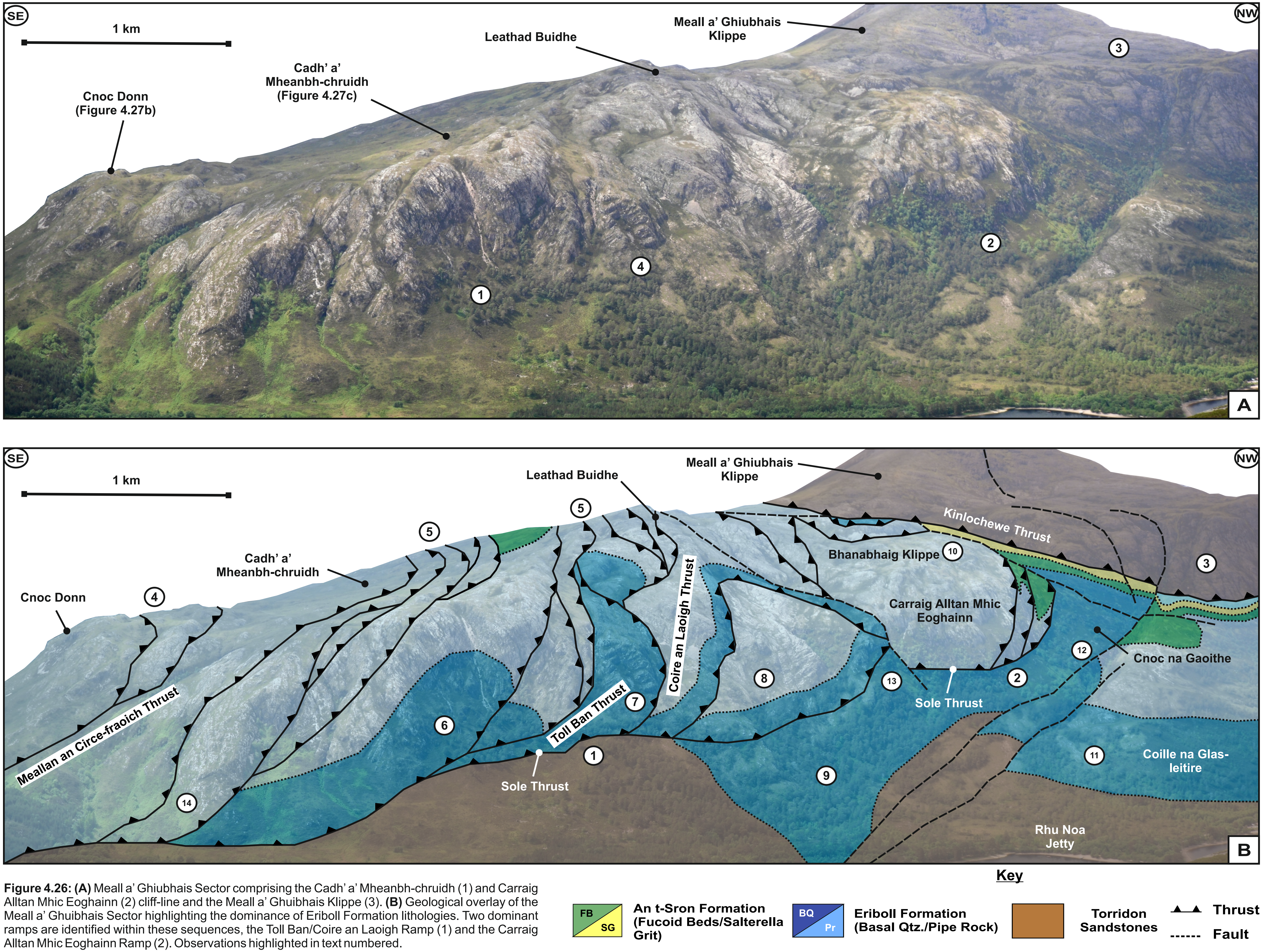


Figure 4.26: **(A)** Meall a' Ghiubhais Sector comprising the Cadh' a' Mheanbh-chruidh (1) and Carraig Alltan Mhic Eoghainn (2) cliff-line and the Meall a' Ghuibhais Klippe (3). **(B)** Geological overlay of the Meall a' Ghuibhais Sector highlighting the dominance of Eriboll Formation lithologies. Two dominant ramps are identified within these sequences, the Toll Ban/Coire an Laoigh Ramp (1) and the Carraig Alltan Mhic Eoghainn Ramp (2). Observations highlighted in text numbered.

4.4.2.1. Cadh’ a’ Mheanbh-chruidh domain

Within the Cadh’ a’ Mheanbh-chruidh domain hinterland, large thrust sheets composed of Eriboll Formation (Pipe Rock Member) units with only a few dominant thrusts present spaced two hundred to four hundred metres apart, such as the Meallan an Circe-fraoich Thrust are observed (Figure 4.25a [8]; 4.26b [4]). Within the hanging-wall of these thrusts, large (ten to twenty metre) shallow-dipping hanging-wall anticlines indicate a broad zone of deformation along dominant map-trace thrusts (Figure 4.27a; 4.27b). Thrusts within this hinterland region place Pipe Rock-on-Pipe Rock, indicating flat-on-flat geometries within a west-northwest to northwest-vergent (i.e., 290 / 300°N) thrust system (Figure 4.25b [1]; 4.26b [4]; 4.27b). Within hinterland regions of the Cadh’ a’ Mheanbh-chruidh domain, shallow-dipping units (20 to 30°) dominate until thrusts are approached creating steeper hanging-wall anticline units (50 to 70°).

South-westward along-strike from observed flat-on-flat geometries, ramp-on-ramp geometries are identified aligned sub-parallel to regional transport with the south-western flank of Doire Dharaich [NH 0023 6239 to NG 9968 6274] indicating a potential sub-décollement transverse structure (Figure 4.25a [9]; 4.25b [2]). Structural and stratigraphical relationships along Doire Dharaich indicate pre-thrust folding exposing Eriboll Formation Basal Quartzites and Pipe Rock units at different levels to thrusting; suggesting a deflection over a potential sub-décollement transverse structure (Figure 4.25a [9]). Thrust propagation through these folds creates ramp-on-ramp geometries observed within fault network analyses. Thrust facing (i.e., lateral thrust climb) within the Doire Dharaich hillside further support pre-thrust folding observations, identifying alternating thrust ramp directions within the footwall and hanging-wall from one side of the fold to the other (Figure 4.25b [2]).

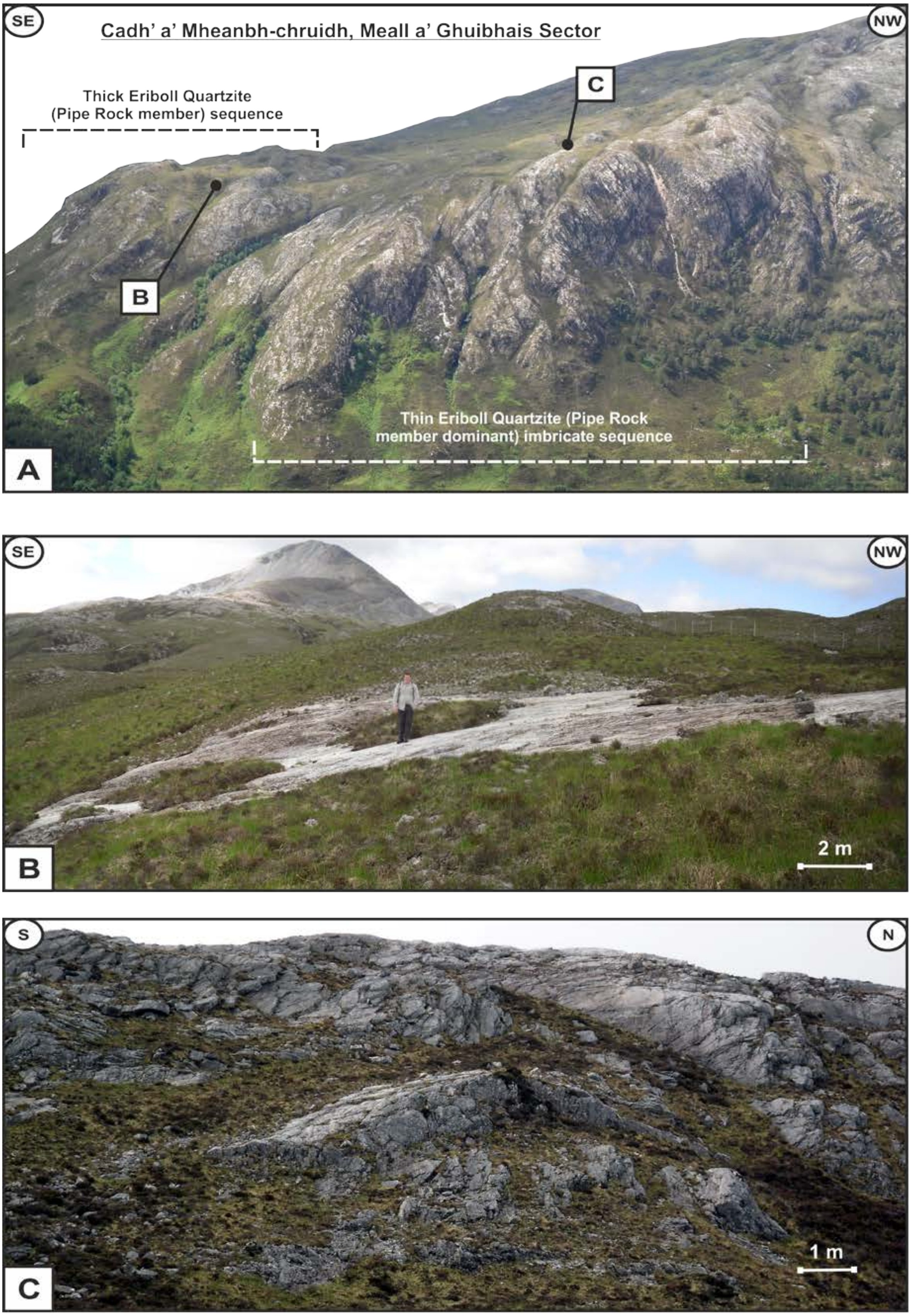


Figure 4.27: (A) Cadh' a' Mheanbh-chruidh domain indicating a thick hinterland Eriboll Formation quartzite dominant sequence characterised by large (10-20 m), shallow hanging-wall anticlines **(B)** indicating a WNW/NW (290/300°N) transport direction. Thin imbricate sequences develop forelandward displaying lateral (N-S) shortening fold structures within the thrust sequence **(C)**. Locations of evidence highlighted within **(A)**.

Large, internally folded hinterland thrust sheets develop forelandward into a sequence of thin imbricates comprising the Coire Domhain and Sgurr na Conghair thrusts before reaching a defuse imbricate zone, termed here the Toll Ban / Coire an Laoigh splay system [NG 9942 6296] (Figure 4.25a [2, 9]; 4.26b [5]). Along-strike this splay system develops from a shallow, diffuse thrust imbricate zone comprising numerous thrust branch-lines (Figure 4.25a [2]; 4.25b [3]), to a system comprising thick, Eriboll Formation quartzite dominant, thrust sheets spaced hundreds of metres apart within the transition zone between the Meall a' Ghiubhais and Benn Eighe sectors linking the Toll Ban and Coire an Laoigh thrusts south-westwards along-strike (Figure 4.25a [10]; 4.25b [4]). Within this splay system, folds between thrust imbricates indicate lateral (north-south) shortening (Figure 4.27c); suggesting transpressional deformation during forelandward-propagation.

Thrust splays comprising the Toll Ban / Coire an Laoigh splay system indicate a bulging of the thrust front within the forelandmost portions of the Cadh' a' Mheanbh-chruidh domain along the Leathad Buidhe Cairn region [NG 9942 6296] (Figure 4.28a). Observations indicate An t-Sron Formation units (Fucoid Beds) smeared along these thrust planes (Figure 4.25a [2]). Addition of these more thinly bedded, fissile units within the Eriboll Formation dominant imbricates allow a much easier slip horizon to be achieved; resulting in a shallow stacking of imbricates (Figure 4.28b).

At the Cadh' a' Mheanbh-chruidh cliff line, the Toll Ban / Coire an Laoigh splay system is observed creating a zone of dominant ramps (termed here the Toll Ban / Coire an Laoigh Ramp) which shows evidence of oscillatory thrusting (Figure 4.26a [1]; 4.26b [1]). Large hanging-wall anticlines containing Eriboll Formation (Basal Quartzites) are truncated by later branching thrusts (Figure 4.26b [6]), indicating a phase of hinterland-propagation. Forelandward of this, within the Toll Ban footwall and Coire an Laoigh Thrust hanging-

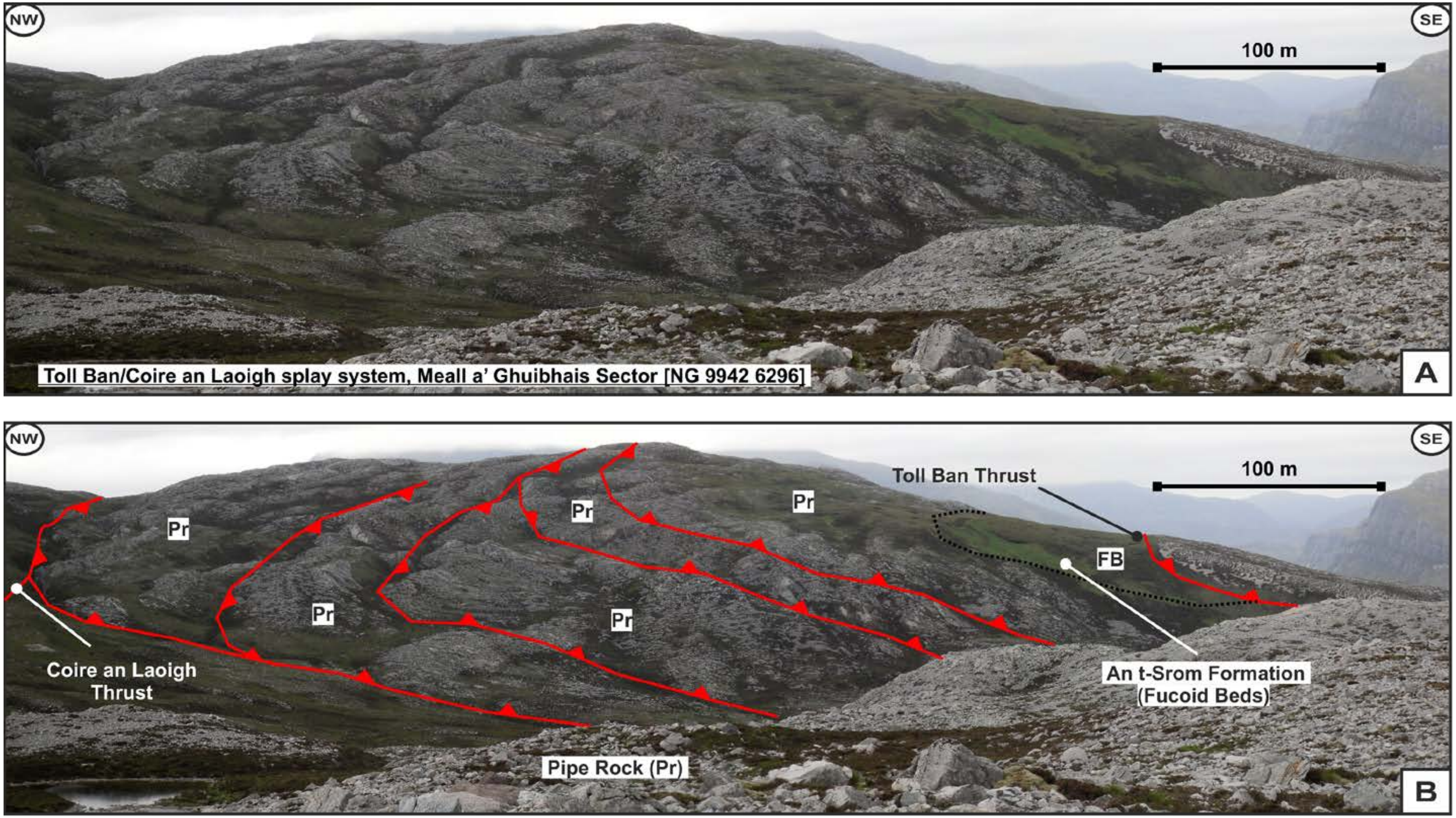


Figure 4.28: **(A)** Toll Ban/Coire an Laoigh splay system within the transition zone between the Cadh' a' Mheanbh-chruidh and Carraig Alltan Mhic Eoghainn domains. **(B)** Structural overlay of the Toll Ban/ Coire an Laoigh splay system. System comprises a series of shallow, thin thrust imbricates within Eriboll Formation (Pipe Rock member) units along which An t-Sron Formation (Fucoid Beds) are smeared; resulting in increased thrust bifurcation. Splay system develops off a series of dominant thrusts (Toll Ban and Coire an Laoigh), which develop from the Sole Thrust along the base of the Cadh' a' Mheanbh-chruidh and Carraig Alltan Mhic Eoghainn cliff-line.

wall, a large axial fold comprising Eriboll Formation (Basal Quartzite) is identified which has been truncated by the overlying Toll Ban Thrust. This indicates a junction along which thrust propagation is alternating between the Toll Ban and Coire an Laoigh thrusts, developing forward into the Carraig Alltan Mhic Eoghainn domain (Figure 4.25a [11]; 4.26a [4]; 4.26b [7]).

Along the base of the Cadh' a' Mheanbh-chruidh cliff line sequence at Allt na Criche [NH 0096 6381], the Sole Thrust is observed cutting down the cliff line placing a two hundred metre, Eriboll Formation quartzite dominant, package onto undeformed foreland Torridonian sandstone units (Figure 4.26b [1]; Figure 4.29). No evidence within this domain supports previous interpretations by Matthews (1984) and Butler *et al.,* (2007) of Torridonian sandstones entrained within these thrust imbricates. Therefore, thrusting along the Torridonian sandstone / Eriboll Formation unconformity interface is suggested.

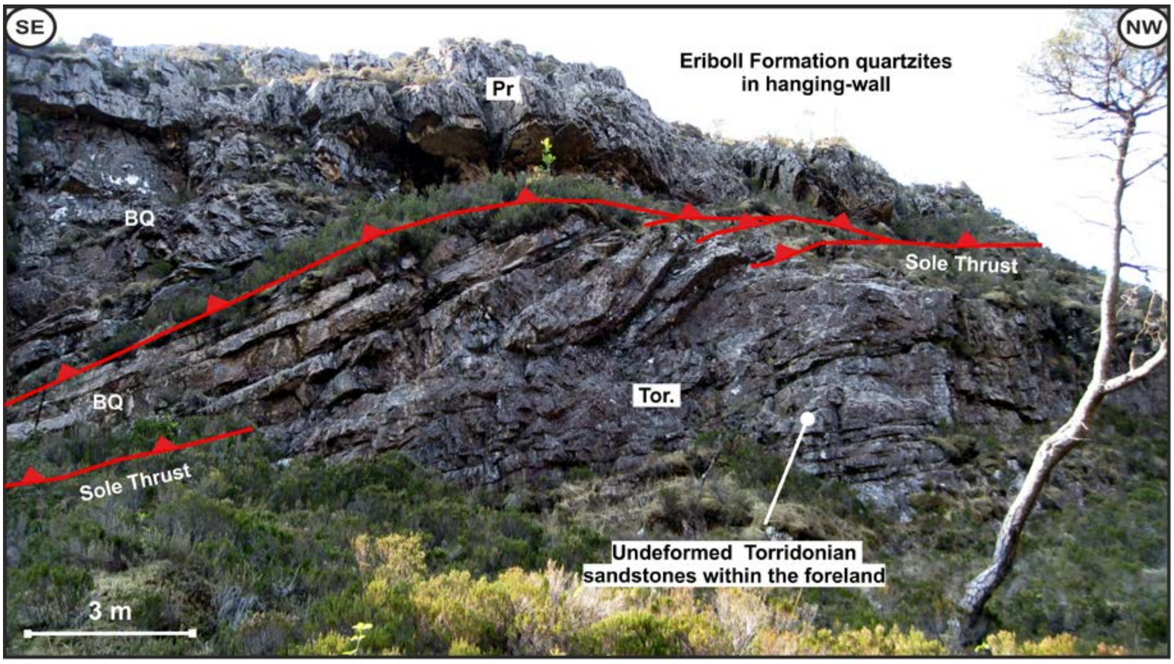


Figure 4.29: Sole Thrust cutting up the Cadh' a' Mheanbh-chruidh cliff-line placing Eriboll Formation lithologies (Basal Qauartzite [BQ] and Pipe Rock [Pr]) onto undeformed Torridonian sandstone [Tor.] foreland, indicating that no Torridonian sandstones are entrained within the thrust imbricates along the Cadh' a' Mheanbh-chruidh or Carraig Alltan Mhic Eoghainn cliff-line.

4.4.2.2. Carraig Alltan Mhic Eoghainn domain

Along the Toll Ban / Corie an Laoigh Ramp front, a drastic structural change is identified (Figure 4.26b [7, 8]; 4.30a). Within the footwall of the Toll Ban / Coire an Laoigh Ramp, a broad (three hundred twenty five metre) syncline (i.e., Alltan Mhic Eogh syncline), containing a large plunging thrust 'lense' is observed (Figure 4.26a [12]; 4.26b [8]; 4.30b; 4.31a). Within the hanging-wall of this thrust 'lense', dominant tens-of-metre scale hanging-wall anticlines are identified, whilst numerous small thrust splays are also viewed within its footwall (Figure 4.30b [1]; 4.31b; 4.31c). These observations form the first visible occurrences of the interaction between the Toll Ban / Corie an Laoigh Ramp and the Carraig Alltan Mhic Eoghainn Ramp at Alltan Mhic Eogh [NG 9990 6402].

Thrust lenses within the Alltan Mhic Eogh footwall syncline indicate an interaction between the cessation of movement within the overlying Toll Ban / Coire an Laoigh Ramp sequence and the development of the Carraig Alltan Mhic Eoghainn Ramp sequence, suggesting simultaneous or oscillating thrust movements along both ramps, potentially as a result of subsurface buttressing. This hypothesis is supported by observations within the foreland beneath the Sole Thrust within the Carraig Alltan Mhic Eoghainn domain which indicate gently folded Torridonian sandstones and Eriboll Formation Basal Quartzites (Figure 4.25a [13]; 4.26b [9]).

Within the Carraig Alltan Mhic Eoghainn domain hinterland, thrust imbricates westward of the Alltan Mhic Eogh footwall syncline to Creagan Ruadh [NG 9832 6263] indicate very shallow-dipping (10 to 30°) Eriboll Formation (Pipe Rock) quartzites over a variety of scales, from tens-of-metre-scale (Figure 4.25a [14]; 4.32a) to metre-scale (Figure 4.25a [15]; 4.32b). Shallow stacking occurs placing imbricates-on-top-of-imbricates as a

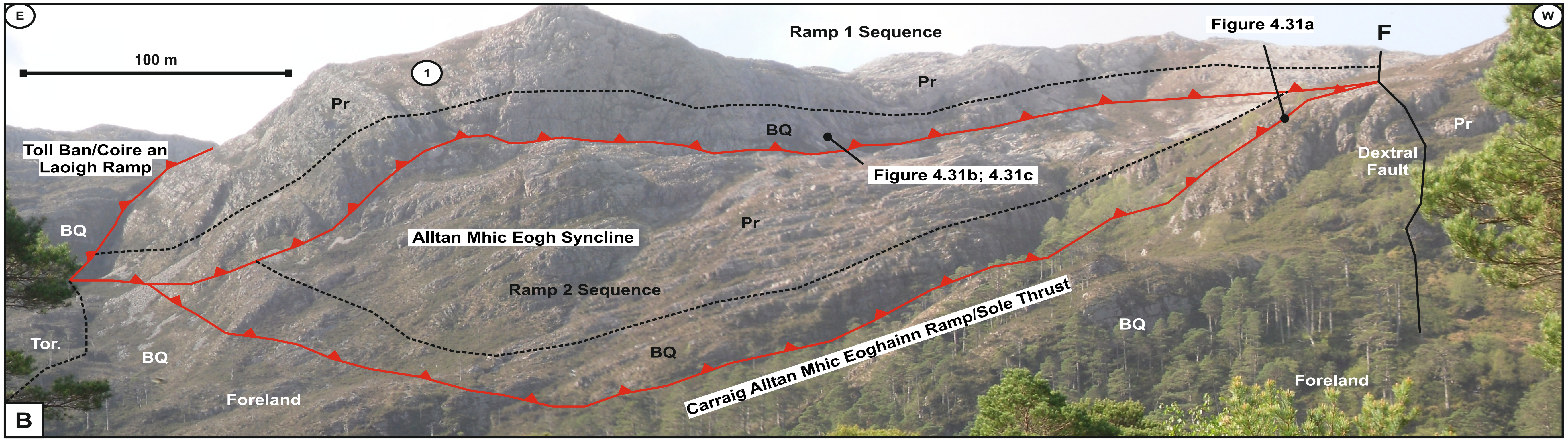


Figure 4.30: (A) Interaction front of the Toll Ban / Coire an Laoigh Ramp with the underlying Carraig Alltan Mhic Eoghainn Ramp along the Alltan Mhic Eogh hillside.

(B) Structural overlay highlighting the interaction between the Toll Ban / Coire an Laoigh Ramp with the underlying Carraig Alltan Mhic Eoghainn Ramp. A large thrust lense is identified within the footwall of the Toll Ban / Coire an Laoigh Thrust identified within map-view by a prominent syncline profile, comprising Eriboll Formation Basal Quartzites and Pipe Rock lithologies. Syncline is underlain by the Sole Thrust which cuts up the Carraig Alltan Mhic Eoghainn hillside through weakly folded Torridonian sandstones and Eriboll Formation lithologies.

Toll Ban / Coire an Laoigh Ramp and Carraig Alltan Mhic Eoghainn Ramp interaction zone, Alltan Mhic Eogh,

Meall a' Ghiubhais Sector [NG 9990 6402]

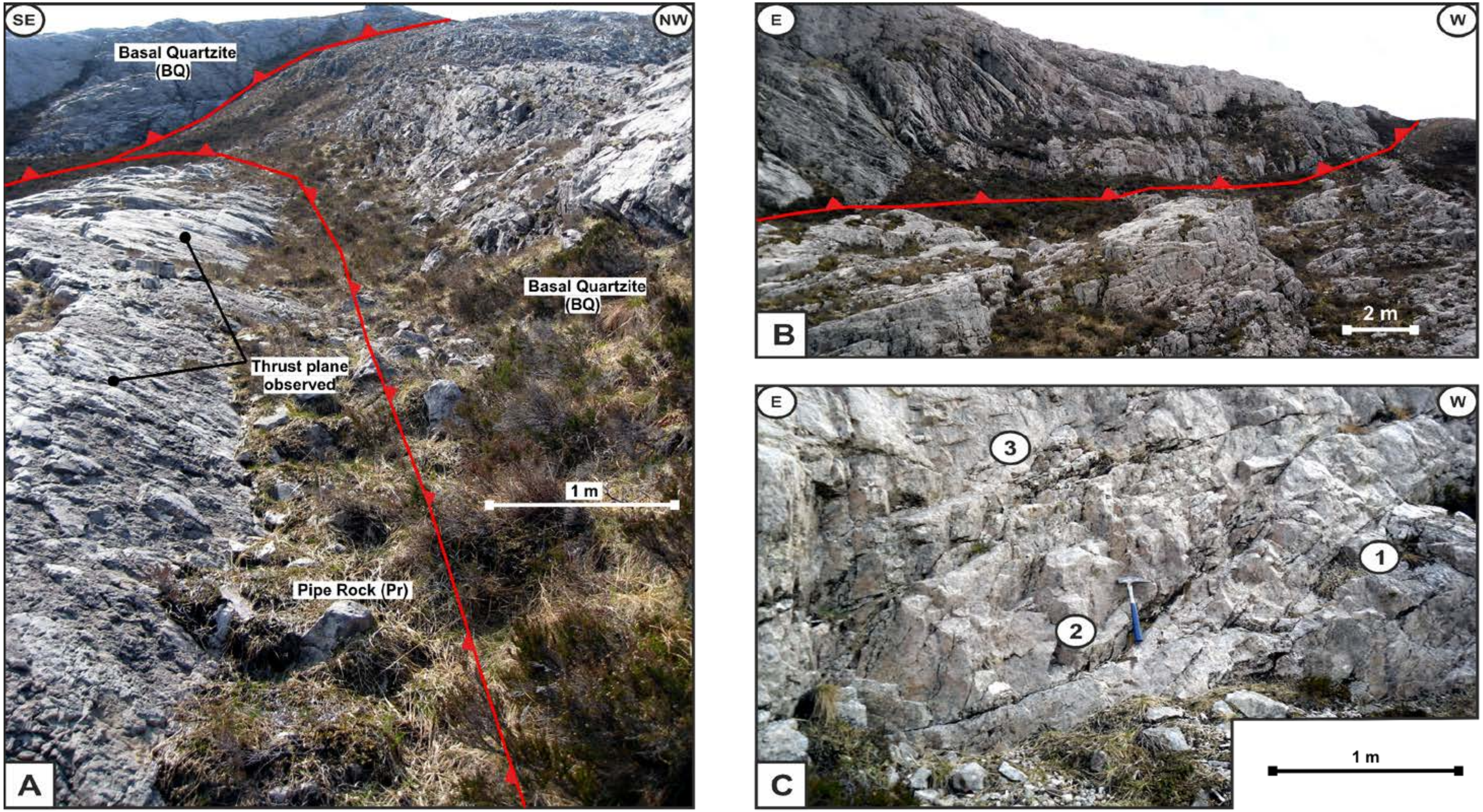


Figure 4.31: (A) Thrust plane identified along the most forelandward (northwestern) edge of the thrust lense indicating a top-to-NW forelandward-propagating system. **(B)** Along the edges of the Alltan Mhic Eogh syncline, large hanging-wall anticlines are identified along the edge of the thrust lense. **(C)** Within the footwall of this thrust lense, along the southeastern edge, a series of footwall splays [1,2,3] are identified. These footwall splays comprise the dominant thrust plane identified within **(B)**.

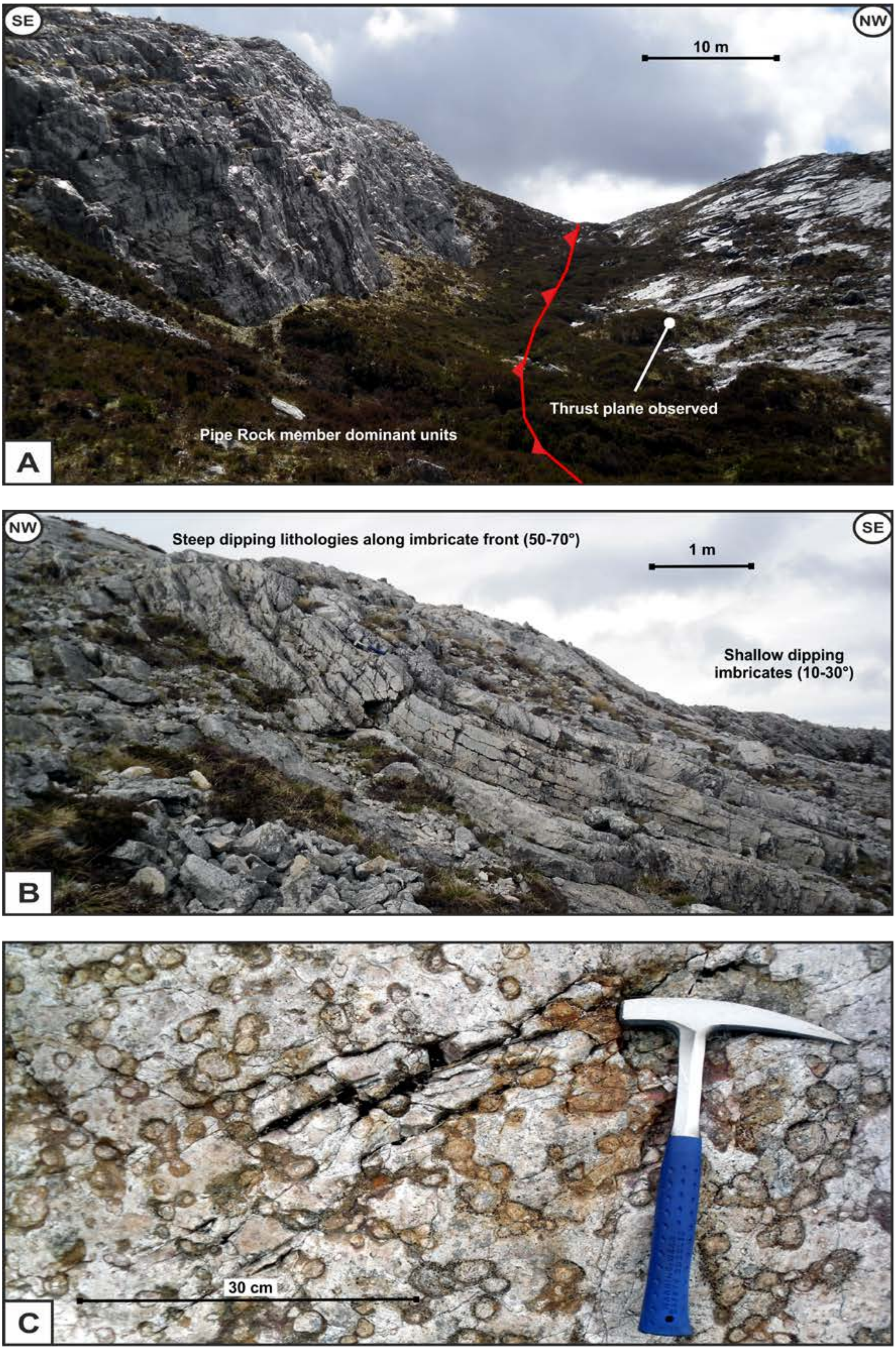


Figure 4.32: Thrust imbricate styles within the Carraig Alltan Mhic Eoghainn domain vary from dominant thrust imbricates over tens-of-metre scales **(A)**, to shallow-dipping (10-30°) imbricates over metre-scales **(B)** which illustrate layer-parallel shearing and shortening. Within thrust imbricates, little internal deformation or strain is observed, evidenced by perfectly preserved *Monocraterion* and *Skolithos* 'pipes' **(C)**.

result of layer-parallel shear, similar to imbricates within the forelandmost sections of the Cadh’ a’ Mheanbh-chruidh domain (Toll Ban / Coire an Laoigh Ramp; Figure 4.28), but on much smaller scales. Thrust imbricates also illustrate little internal deformation as a result of this process, evidenced by undeformed *Monocraterion* and *Skolithos* ‘pipes’ which indicate very little strain within the imbricate system (Figure 4.32c).

Along-strike at Creagan Ruadh [NG 9864 6295], broad (open) folds are identified within the hanging-walls of thick imbricate packages along-strike, supporting the regional (290 / 300°) transport direction within this region (Figure 4.34a). Fold styles develop north-eastwards into tight folds with varying axial traces within the north-western Loch Allt an Daraich region [NG 9869 6362] (Figure 4.34b), indicating increased deformation northwards towards the Loch Maree Fault and north-westwards within the (290 / 300°) transport direction towards the Meall a’ Ghiubhais Klippe sequence.

Along the Carraig Alltan Mhic Eoghainn domain cliff-line, forelandward of the Alltan Mhic Eogh footwall syncline, these drastic along-strike changes in deformation style are most clearly expressed in the form of large hanging-wall antiforms orientated east-west to north-south (Figure 4.33a). No underlying thrusts are observed, suggesting that large antiforms comprise a thick folded sequence within the Carraig Alltan Mhic Eoghainn Ramp hanging-wall, within which layer-parallel shear and elements of buttressing are viewed [NG 9950 6414] (Figure 4.25a [16]; 4.33a; 4.33b). Hanging-wall antiforms and fold axial-traces within the Alltan Mhic Eogh footwall syncline are also discerned, although these are truncated by the thrust lense; indicating a pre-thrust folding phase. Plunging nature of the thrust lense also suggests that a second deformation phase overprints this thrust, further supporting fold observations within the underlying foreland (Figure 4.25a [12, 13]; 4.26b [8]).

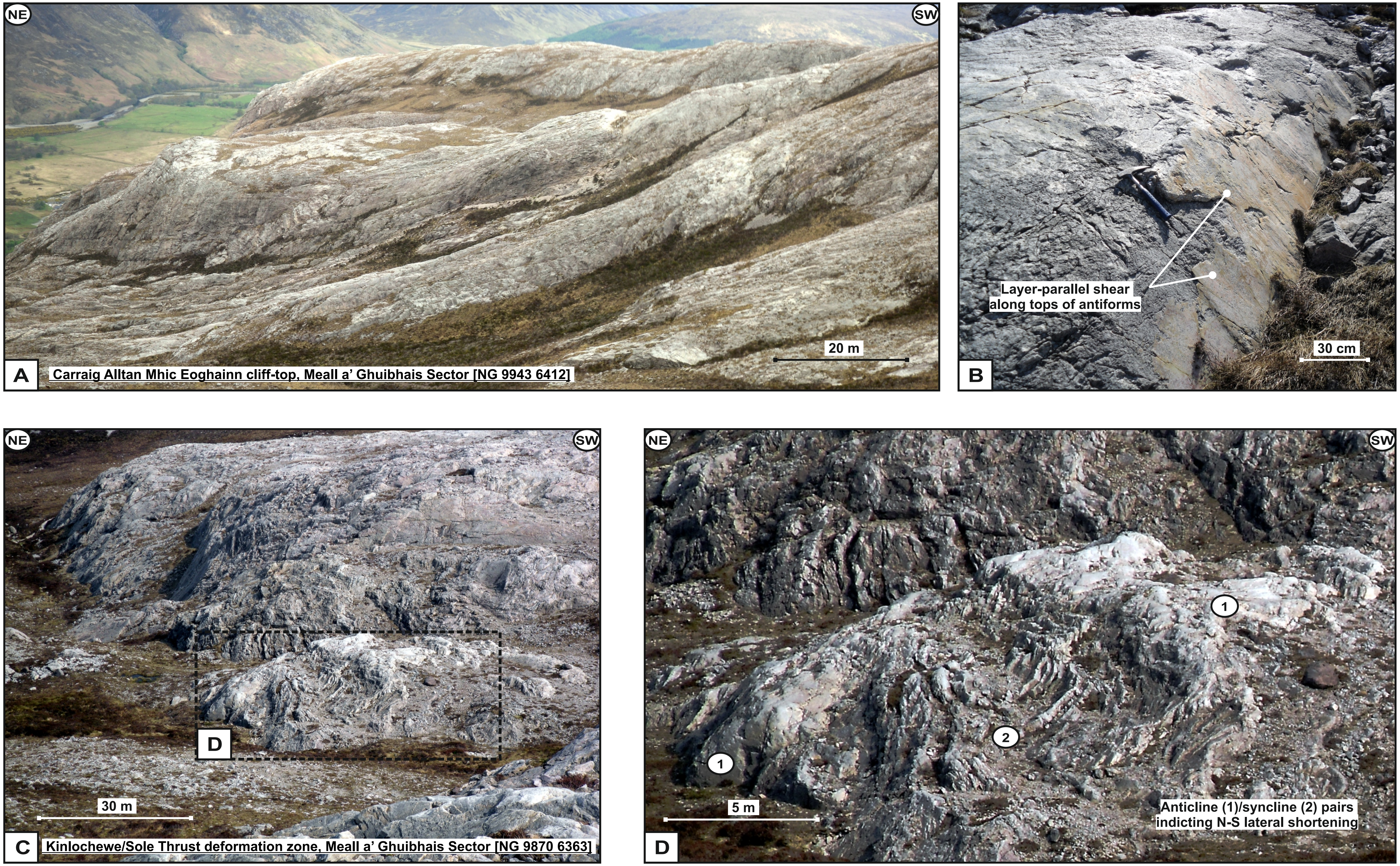


Figure 4.33: Along the top of the Carraig Alltan Mhic Eoghainn cliff-line, large antiforms are identified with no visible underlying thrusts **(A)**. These large antiforms compose the hanging-wall of the Carraig Alltan Mhic Eoghainn Ramp, displaying layer-parallel shear along their surfaces (B). Within the front of the Meall a' Ghiubhais Klippe, a 500 m zone of heavily fractured and deformed Eriboll Formation (Pipe Rock) is observed **(C)**. Within these units anticline/syncline pairs are identified indicating lateral (N-S) shortening **(D)**.

Carraig Alltan Mhic Eoghainn Ramp cliff-line deformation zones

Meall a' Ghiubhais Sector [NG 9836 6401 to NG 9870 6363]

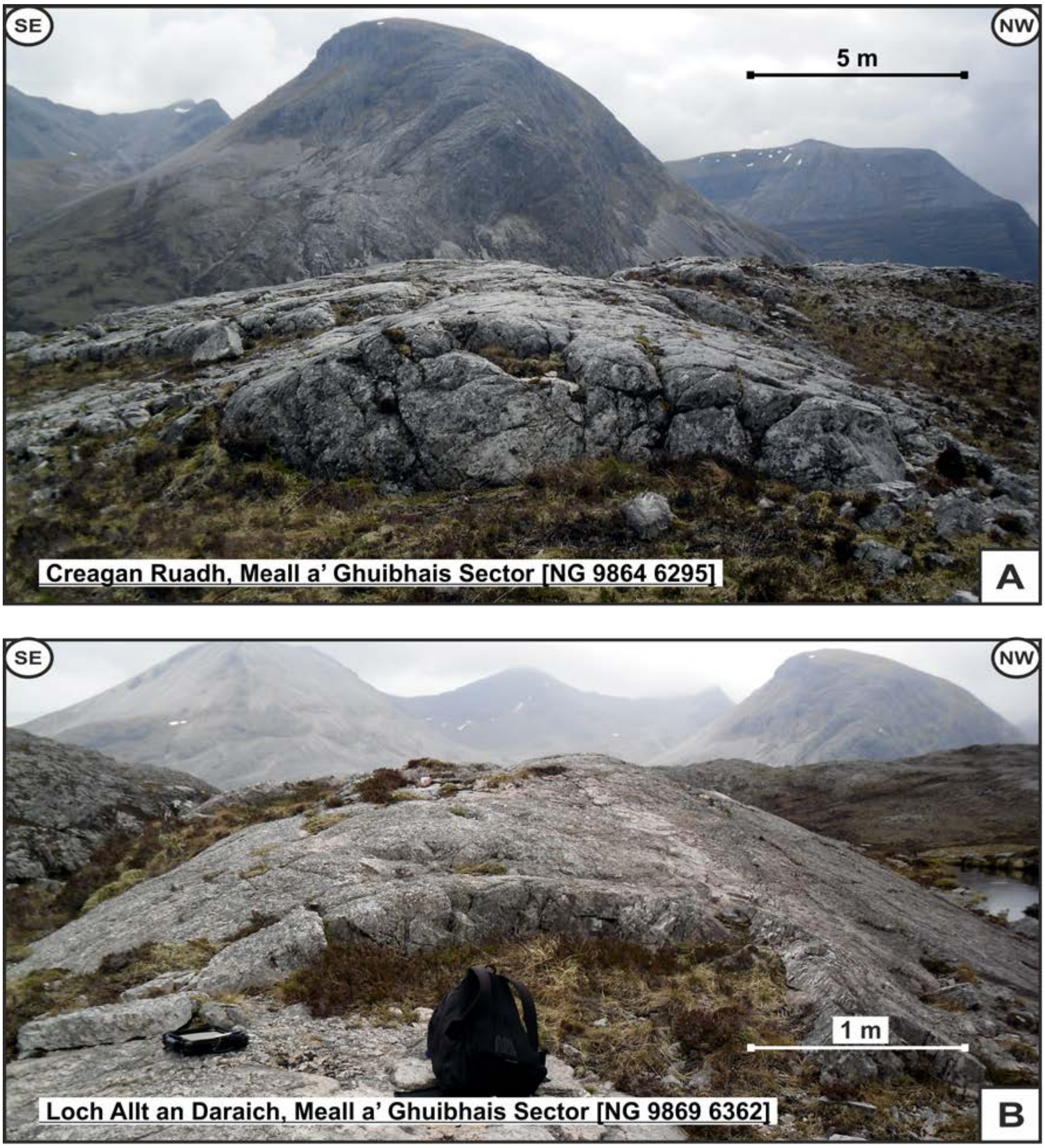


Figure 4.34: (A) Within the Creagan Ruadh region, broad (open) folds are identified within the hanging-walls of thick imbricate packages along-strike, supporting the regional (290 / 300°) transport direction. Fold styles develop north-eastwards into tight folds with varying axial traces within the north-western Loch Allt an Daraich region **(B)**, indicating increased deformation northwards towards the Loch Maree Fault and north-westwards within the (290 / 300°) transport direction towards the Meall a' Ghiubhais Klippe sequence.

Overlying this zone of deformation, interactions between lower and higher Eriboll Formation dominant thrust sheets are identified producing a small Eriboll Formation klippe along the base of the Meall a' Ghiubhais Klippe [NG 9836 6401] (Figure 4.25a [16]; 4.26b [10]). This Eriboll Formation dominant klippe, named here as the Bhanabhaig Klippe (after Loch Bhanabhaig), is focused within a five hundred metre zone of heavily fractured Eriboll Formation (Pipe Rock) quartzites. Lateral (north-south) shortening within numerous anticline-syncline pairs is observed within this zone (Figure 4.33c; 4.33d) [NG 9870 6363], whilst further anticline-syncline pairs are also discerned with axial-traces independent of the regional (290 / 300°) transport direction.

This region is identified as the interaction zone between the down-cutting Kinlochewe Thrust, which forms the roof to the Eriboll Formation dominant footwall imbricate sequence carrying Torridonian sandstones (which comprise the Meall a' Ghiubhais Klippe), and the Sole Thrust Zone, which cuts up the Carraig Alltan Mhic Eoghainn cliff-line (Figure 4.25a [16, 17]). Map patterns within this five hundred metre zone identify thrusts which cross-cut each other, suggesting out-of-sequence interactions. The Bhanabhaig Klippe itself is suggested to be produced as a result of footwall interactions within the down-cutting Kinlochewe Thrust, which appears to load and down-warp underlying lithologies within the five hundred metre zone; observations supported by fault network analyses which indicate a long hanging-wall ramp profile encompassing the top of the Bhanabhaig Klippe (Figure 4.25b [4]).

Further evidence in support of interactions between the down-cutting Kinlochewe Thrust and the Sole Thrust can be identified at the base of the Carraig Alltan Mhic Eoghainn cliff-line, within the forelandmost reaches of the Carraig Alltan Mhic Eoghainn Ramp (Figure 4.35a; 4.35b). Here the Sole Thrust is observed climbing the cliff-line towards the Meall a' Ghiubhais Klippe, cutting-up stratigraphically within its hanging-wall from Eriboll Formation (Pipe Rock) dominant units into repetitions of An t-Sron Formation lithologies (Fucoid Bed and Salterella Grit units) [NG 9923 6434] (Figure 4.25a [4]; 4.26a [3]; 4.26b [2]; 4.35a; 4.35b); observations supported by thrust facing along hanging-wall and footwall ramps

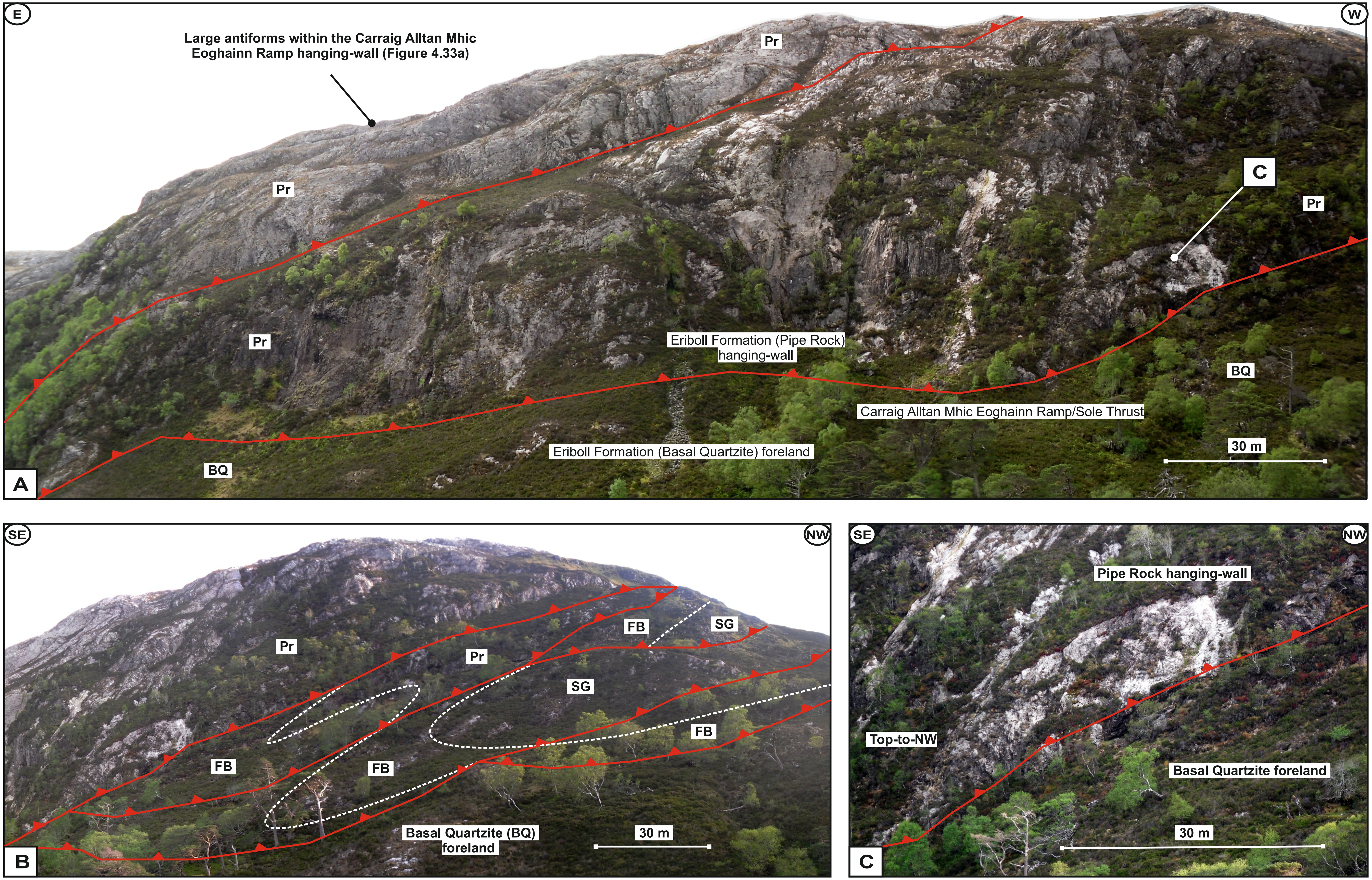


Figure 4.35: Base of Carraig Alltan Mhic Eoghainn cliff-line, within the forelandmost reaches of the Carraig Alltan Mhic Eoghainn Ramp. Sole Thrust is observed climbing cliff-line towards the Meall a' Ghiubhais Klippe, cutting-up stratigraphically within its hanging-wall from Eriboll Formation (Pipe Rock [Pr]) dominant units into repetitions of An t-Sron Formation lithologies (Fucoid Bed [FB] and Salterella Grit [SG] units) **(A, B)**. Hanging-wall anticlines supporting a top-to-NW (290 / 300°) regional transport direction **(C)**.

Carraig Alltan Mhic Eoghainn Ramp / Sole Thrust climbing up cliff-line

Carraig Alltan Mhic Eoghainn, Meall a' Ghiubhais Sector [NG 9923 6434]

within fault network analyses (Figure 4.25b [5]). Bedding within these An t-Sron Formation imbricates is steep (60 to 70°), whilst internal folding is also observed. Hanging-wall anticlines supporting a forelandward-propagating west-northwest to northwest (290 / 300°) transport direction are also indicated within the more competent hanging-wall Eriboll Formation (Pipe Rock) units (Figure 4.35c). The Sole Thrust as a whole within the Meall a' Ghiubhais sector gradually climbs stratigraphically from Eriboll Formation (Basal Quartzites) to An t-Sron Formation units within forelandmost portions of the Carraig Alltan Mhic Eoghainn Ramp, maintaining a consistent two hundred metre thick imbricate profile within the Kinlochewe Thrust footwall. No Torridonian sandstones are entrained within the thrust system (Figure 4.26b [1, 2]).

Lower slopes beneath the Sole Thrust are weakly folded, but otherwise undisturbed foreland successions of Eriboll Formation quartzites and Torridonian sandstones (Figure 4.25a [13]; 4.26b [9, 11]). Summit areas within Coille na Glas-Leitire [NG 9960 6484] are in the basal part of the Pipe Rock Member, Basal Quartzite below and topmost part of Torridonian (Applecross Formation) sandstones to the Loch Maree shore, seen at Rhu Nòa Jetty [NH 0046 6478] (Figure 4.25a [18]; 4.26b [11]). Open upright folding deforms the foreland sequence in broad northeast to southwest trending warps; suggest a potential blind basal thrust beneath this sequence (i.e., new proto-ramp which has failed to develop). Development of these folded foreland sequences could be in response to interactions with vertical faults running through the east-southeast to west-northwest-trending Allt na h-Alrighe / Cnoc na Gaoithe gorge [BNG 9935 6459] (Figure 4.25a [19]; 4.26b [12]; 4.36). This structure could potentially be the next proto-ramp which failed to develop as a result of Sole Thrust interaction within the down-cutting Kinlochewe roof-thrust above which dives under the base of the Meall a' Ghiubhais Klippe sequence.

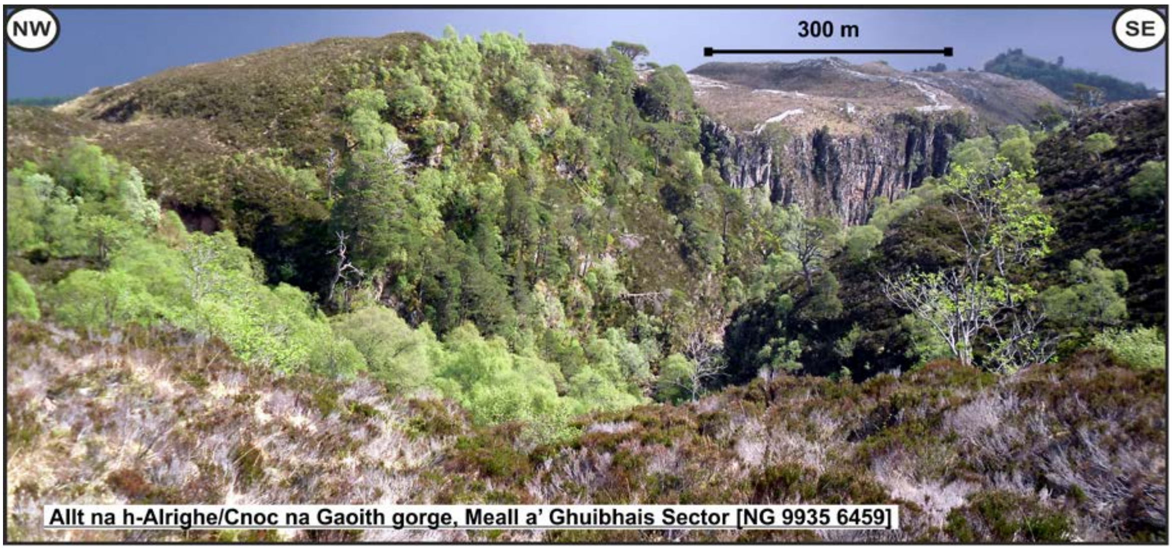


Figure 4.36: ESE-WNW-trending Allt na h-Alrighe/Cnoc na Gaoithe gorge within which vertical faults are observed. Foreland interactions with these faults could be the cause for folded Torridonian sandstone / Eriboll Formation foreland sequences beneath the Carraig Alltan Mhic Eoghainn cliff-line. Scale relevant to far side of gorge.

Later dextral faulting, indicated by slickenside grooves within Pipe Rock units, also slice the Carraig Alltan Mhic Eoghainn domain along the north-western wall of the Alltan Mhic Eogh footwall syncline [NG 9979 6420]; cross-cutting hanging-wall anticlines and dropping the Sole Thrust one hundred metres lower down the Carraig Alltan Mhic Eoghainn cliff-line (Figure 4.26b [13]; 4.37a-c). This indicates that later stage developments, both here and forelandward into the Allt na h-Alrighe / Cnoc na Gaoithe gorge and Meall a' Ghiubhais Klippe domain, are dominated by brittle fault processes. Along the top of the cliff-line, angles within the dextral fault increase from shallowly dipping (30°) to vertical within lower cliff-line sections (Figure 4.37a; 4.37b).

Fault network analyses indicate that within the Carraig Alltan Mhic Eoghainn domain, few thrust ramp map-traces are determined, with the only notable exceptions including thrust ramps south of the Cnoc na Gaoithe fault system within the foreland, and complexities within the Carraig Alltan Mhic Eoghainn region [NG 9916 6432] (Figure 4.25b [4, 5]). Furthermore, branch-lines and fault-tip line map-trace analyses indicate a dominance of

Figure 4.37: Dextral faulting, indicated by slickenside grooves within Pipe Rock units, cross-cut the Carraig Alltan Mhic Eoghainn domain along the north-western wall of the Alltan Mhic Eogh footwall syncline **(A, B)**; cross-cutting hanging-wall anticlines **(C)**, whilst also dropping the Sole Thrust 100 m lower down the Carraig Alltan Mhic Eoghainn cliff-line. This indicates that brittle fault processes dominate later stage developments within this domain. Along the top of the cliff-line, angles within the dextral fault increase from shallowly dipping (30°) to vertical within lower cliff-line sections .

branch-lines off the Sole Thrust (Figure 4.25b [3, 5, 6]), with no fault-tip lines present within the Carraig Alltan Mhic Eoghainn domain and only a few within the Carraig Alltan Mhic Eoghainn domain; indicating that the Loch Maree southern wall within the Meall a' Ghiubhais sector is a dominant thrust bifurcation zone. Limited thrust ramps were expected to be identified within fault network analyses of the Loch Maree southern wall along the Cadh' a' Mheanbh-chruidh and Carraig Alltan Mhic Eoghainn cliff-line however, due to the dominance of Eriboll Formation quartzites within the two hundred metre footwall imbricate package.

4.4.2.3. Meall a' Ghiubhais Klippe domain

The Meall a' Ghiubhais Klippe rests on the foreland-dipping frontal part of the Carraig Alltan Mhic Eoghainn domain; on the broader scale lying on the west-northwest-dipping flank of the Achnashellach Culmination (Figure 4.26b [3]; 4.38). The Klippe is composed of two hundred fifty metre normal, right-way-up successions of red-brown weathering Torridonian sandstones (Applecross Formation). Units comprise the hanging-wall of the

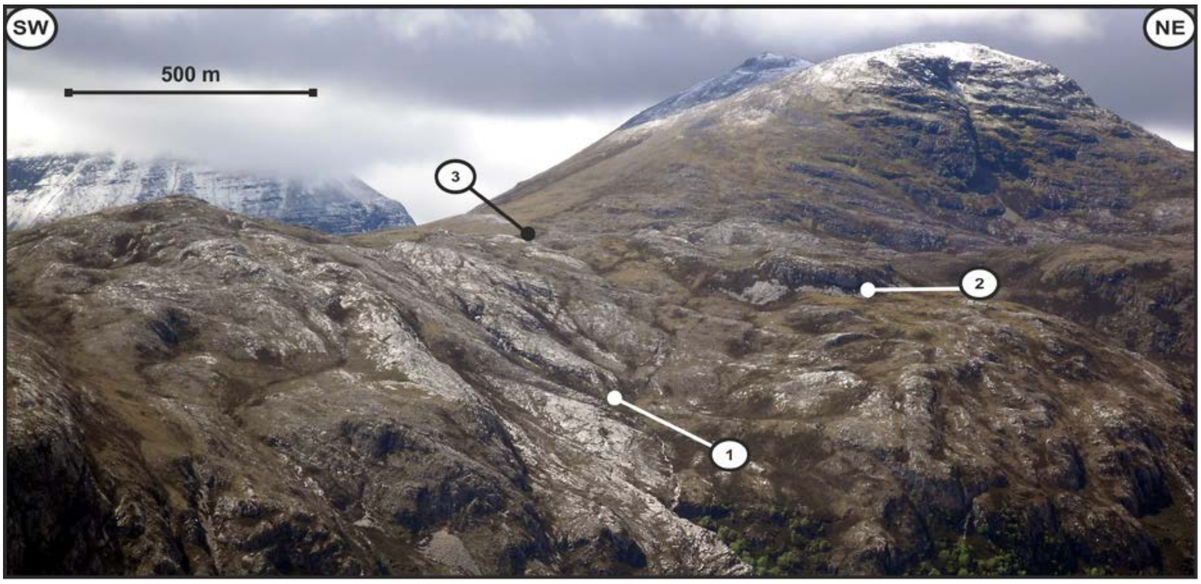


Figure 4.38: Meall a' Ghiubhais Klippe (facing WNW). Klippe sequence rests on the foreland-dipping frontal part of the Carraig Alltan Mhic Eoghainn domain which comprises large hanging-wall antiforms (Alltan Mhic Eogh syncline [1]), and the 500 m interaction zone beneath the Kinlochewe Thrust, upon which the Meall a' Ghiubhais Klippe resides (i.e., Eriboll Formation dominant Bhanabhaig Klippe [2], and the heavily fractured Eriboll Formation (Pipe Rock) quartzites [3]).

Kinlochewe Thrust which forms the roof thrust to the underlying Eriboll Formation quartzites and An t-Sron Formation imbricate sequences identified within the Cadh' a' Mheanbh-chruidh and Carraig Alltan Mhic Eoghainn domains. Previous interpretations within this region by Matthews (1984) and reported by Butler *et al.,* (2007) suggest large amounts of older Diabaig Formation lithologies comprising the lower reaches of the Meall a' Ghiubhais Klippe, an observation not supported here. No evidence for Diabaig lithologies are observed within the Meall a' Ghiubhais Klippe sequence.

Structural complexities are identified within the south-western regions of the Klippe, where footwall thrusts containing slices of Eriboll quartzites, Torridonian sandstones and Lewisian basement gneisses are identified, indicating an imbricate sequence cutting structurally down (stratigraphically up; Figure 4.25a [20]; 4.39a-c). Foreland lithologies underlying these thrust splays also appear to warp (Figure 4.39c [1]), suggesting a potential sub-décollement transverse structure within the Cadh' a' Mheanbh-chruidh and Carraig Alltan Mhic Eoghainn domains which is developed forelandward into the Meall a' Ghiubhais Klippe. Interactions of these imbrications are aligned with footwall An-t-Sron Formation imbricates at the Kinlochewe Thrust / Sole Thrust interaction zone [NG 9791 6283] and ramp-on-ramp geometries observed at Doire Dharaich [NH 0023 8623], further supporting this hypothesis (Figure 4.25a [2, 5, 9, 20]; 4.25b [2, 7, 8]). Structurally lower An t-Sron Formation imbricates are cut off by the basal thrust to the Klippe (Kinlochewe Thrust) indicating an out-of-sequence element to the front of the Meall a' Ghiubhais sector (Figure 4.25a [5, 15, 17]), supporting observations within the Carraig Alltan Mhic Eoghainn domain.

Along the base of the Klippe, small bodies of Lewisian gneisses are observed, locally forming the basement to the overlying Torridonian, as denoted in Butler *et al.,* (2006;

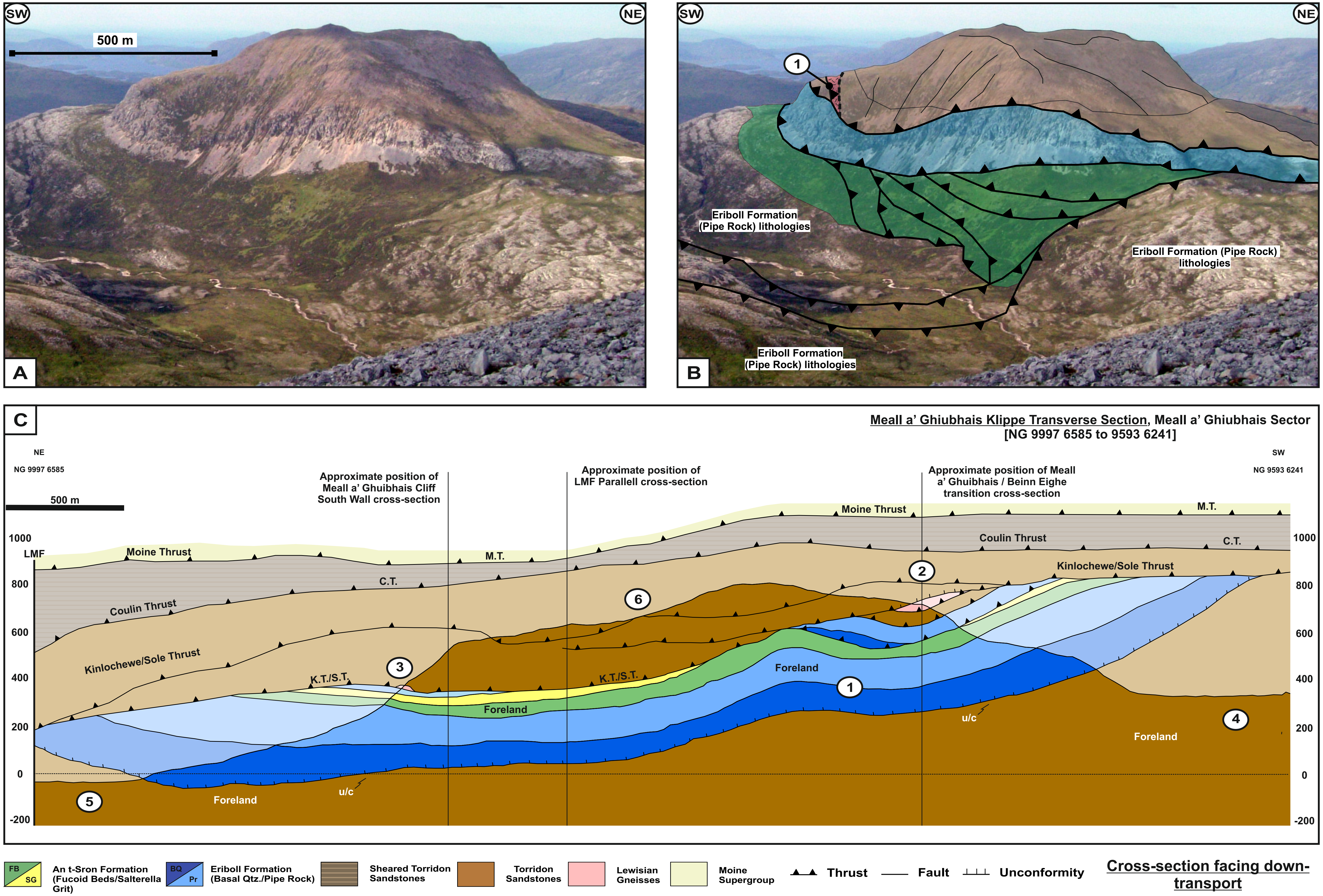


Figure 4.39: (A) Meall a' Ghiubhais Klippe facing NW within transport direction (i.e., up-transport). **(B)** Geological overlay of the Meall a' Ghuibhais Klippe. Kinlcohewe/Sole Thrust cuts higher along the south-western edge than that observed within the north-western side. Lewisian gneiss 'pip' localities are identified. An t-Sron Formation imbricates within the front of the Meall a' Ghuibhais Klippe are truncated by higher thrusts containing Eriboll Formation (Pipe Rock) lithologies. **(C)** Transport-transverse cross-section through the Meall a' Ghiubhais Klippe sequence. Cross-section illustrates the cross-strike behaviour of the Kinlochewe/Sole Thrust, from a splay series containing Lewisian gneisses to Eriboll Formation quartzites within its south-western edge, to a single thrust plane comprising Torridonian sandstones at the Loch Maree Fault (LMF). Foreland Torridonian sandstones also indicate a non-uniform stratigraphical deposition (400m within SW to 0 m at LMF). Such an along-strike variation may be the result of a deflection over a pre-thrust sub-decollement transverse structure or a pre-thrust stratigraphical variation. Observations numbered within text highlighted.

2007). The largest of these is exposed on the south-west corner of the Klippe [NG 9710 6325] (Figure 4.39b [1]; 4.39c [2]; 4.40), where a two hundred metre slice of Lewisian gneisses has been thrust over a thin slice of Torridonian sandstones. Gneisses are bounded above by the sub-Torridonian unconformity. Gneisses display little internal deformation, apart from along the thrust contact where lower units indicate localised veins being folded and sheared within the west-northwest to northwest (290 /300°N) transport direction (Figure 4.40). More Lewisian rocks are found along the northern edge of the Klippe [NG 9840 6522] (Figure 4.39c [3]). These small pips, again bounded above by the sub-Torridonian unconformity and below by the Kinlochewe Thrust, are interpreted as palaeohills in the Precambrian landscape, planed off by the Kinlochewe Thrust during its development; supporting previous interpretations by Matthews (1984) and Butler *et al.,* (2007).

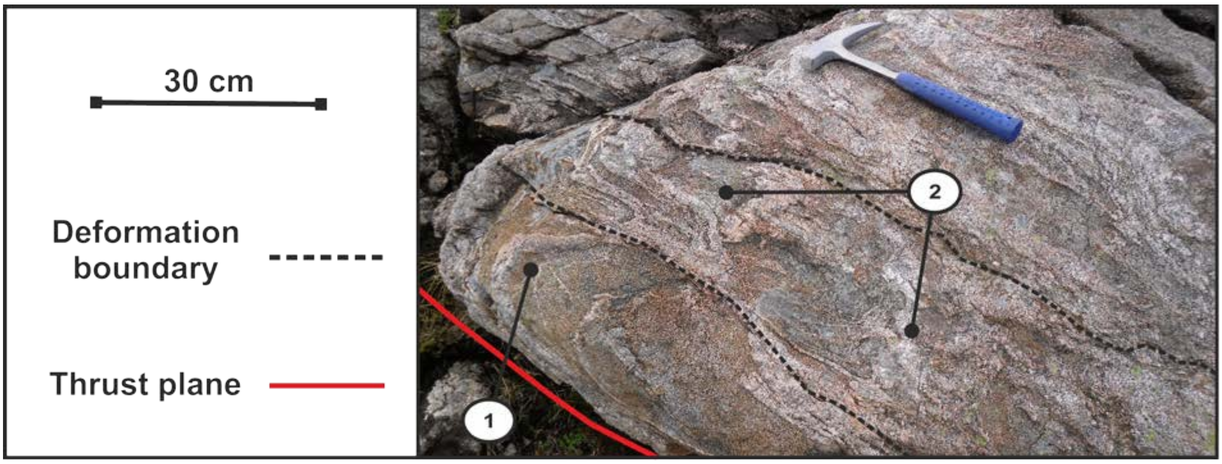


Figure 4.40: Lewisian gneiss 'pips' within the Meall a'Ghiubhais Klippe sequence. Within the lower gneisses, along the thrust splay contact, localised folded (1) and sheared (2) veins are observed supporting the WNW to NW (290 / 300°N) transport direction. Higher Lewisian gneisses indicate little internal deformation.

Along the eastern side of the Meall a' Ghiubhais Klippe, the Sole Thrust cuts two hundred metres lower on the southern Loch Maree sidewall indicating angled thrusting creating a saucer shaped thrust plane through the base of the Klippe sequence, which is offset by later dextral faults of the east-southeast to west-northwest-trending Allt na h-Alrighe /

Cnoc na Gaoithe gorge sequence (Figure 4.25a [7]; 4.39c [2, 3]; 4.41a). Furthermore, Torridonian sandstone levels within the undeformed foreland indicate a distinct cross-strike topographical discontinuity dropping from four hundred metres to zero metres at the Loch Maree shoreline, indicating a non-planar Torridonian deposition surface (Figure 4.39c [4, 5]). These observations support the identification of a potential pre-thrust, sub-décollement transverse structure and / or pre-thrust cross-strike stratigraphical discontinuity which has caused differential deflections within the transport path of the Kinlochewe roof thrust.

The Kinlochewe / Sole Thrust plane itself comprises a splayed network of thrusts deforming the overlying Applecross Formation Torridonian sandstone hanging-wall [NG 9896 6444], whilst cutting up-and-down stratigraphical section within the footwall sequence (Figure 4.39c [2, 3, 6]; 4.41b; 4.41c). Supportive outcrop evidence indicating the Kinlochewe / Sole Thrust changing stratigraphical level can be identified along the north-eastern side of the Meall a' Ghiubhais Klippe from Allt Bhanabhaig [NG 9887 6403] to Furan Mòr [NG 9763 6528] (Figure 4.25a [21]; 4.39c [3]). In upper Allt Bhanabhaig the footwall lies in Eriboll Formation quartzites to Torridonian sandstones (Figure 4.41b; 4.41c); at Cnoc na Gaoithe [NG 9899 6458], An t-Sron Formation Fucoid Beds. The thrust continues to climb up-section north-westwards into the lower part of the Durness Group, whilst still further west, dropping back down onto An t-Sron Formation Salterella Grit units (Figure 4.25a [21]).

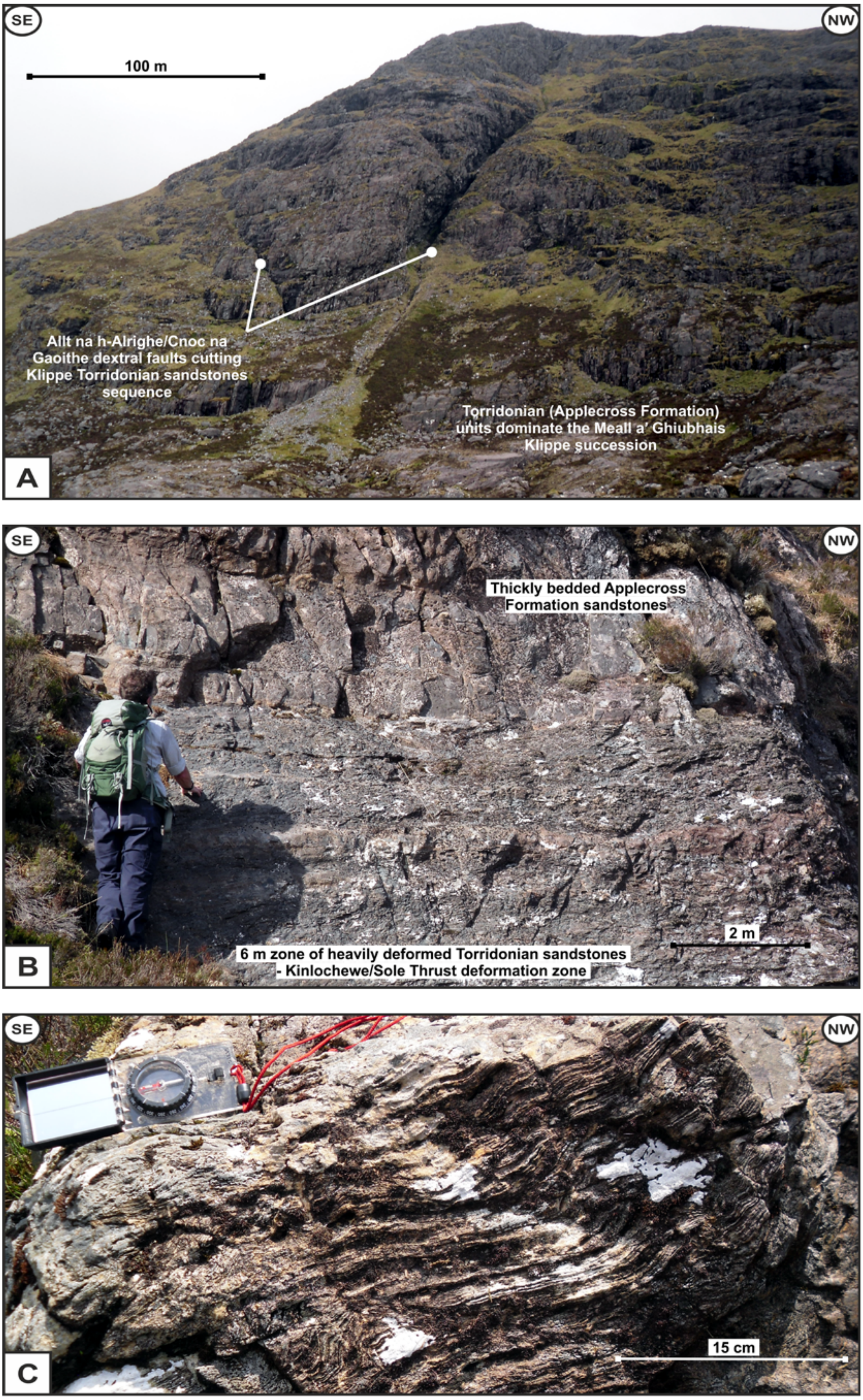


Figure 4.41: (A) Allt na h-Alrighe / Cnoc na Gaoithe dextral fault system cutting the Meall a' Ghuibhais Klippe sequence comprising the Kinlochewe/Sole Thrust hanging-wall. **(B)** Kinlochewe / Sole Thrust creates a prominent 6 m deformation zone within hanging-wall Torridonian sandstones. **(C)** Heavily deformed and sheared hanging-wall Torridonian sandstones. Nature of Torridonian sandstones (i.e., Applecross Formation or Diabaig Formation) unknown, however, no Diabaig lithologies found locally.

4.4.2.4. Meall a' Ghiubhais Sector: Cross-strike three-dimensional distribution

Map patterns identified within Figure 4.25a; 4.26b and field observations described within previous sections clearly identify a series of transport-lateral and transport-parallel discontinuities within the Meall a' Ghiubhais sector, from the hinterland Cadh' a' Mheanbh-chruidh domain to the forelandmost Meall a' Ghiubhais Klippe domain. Cross-strike map patterns and cross-sections (located on Figure 4.1; 4.25a), indicate a northeast-southwest trending cross-strike discontinuity resulting in a dramatic geometrical change from a thick eight hundred metre structural package of Eriboll Formation quartzites and Torridonian sandstones within the Beinn Eighe Massif sector, to a two hundred metre 'flap-like' structural package comprising Eriboll Formation quartzites and An t-Sron Formation lithologies within the Sole Thrust hanging-wall along the Cadh' a' Mheanbh-chruidh / Carraig Alltan Mhic Eoghainn cliff line. A series of structural discontinuities are also identified orientated sub-parallel to regional transport (i.e., 290 / 300°), indicating a distinct forelandward architectural change between the Cadh' a' Mheanbh-chruidh and Meall a' Ghiubhais Klippe domains.

Within the hinterland Cadh' a' Mheanbh-chruidh domain, a series of dominant thrusts spaced two hundred to four hundred metres apart, such as the Meallan na Circe-fraoich Thrust, are viewed carrying two hundred metre thick repetitions of Eriboll Formation quartzites within their hanging-walls; totalling a four hundred metre thick structural package (Figure 4.42a [1]). Individual thrust sheets are dominated by either Eriboll Formation Basal Quartzites or Pipe Rock units, creating flat-on-flat geometries within fault network analyses (Figure 4.25b [1]). Observations indicate a rise in the décollement level from Eriboll Formation Basal Quartzites to Pipe Rock lithologies within this domain as thrusts propagate along this higher detachment and along the Eriboll Formation (Basal Quartzite) / Torridonian sandstone interface (Figure 4.42a [1, 2]). A small frontal step is

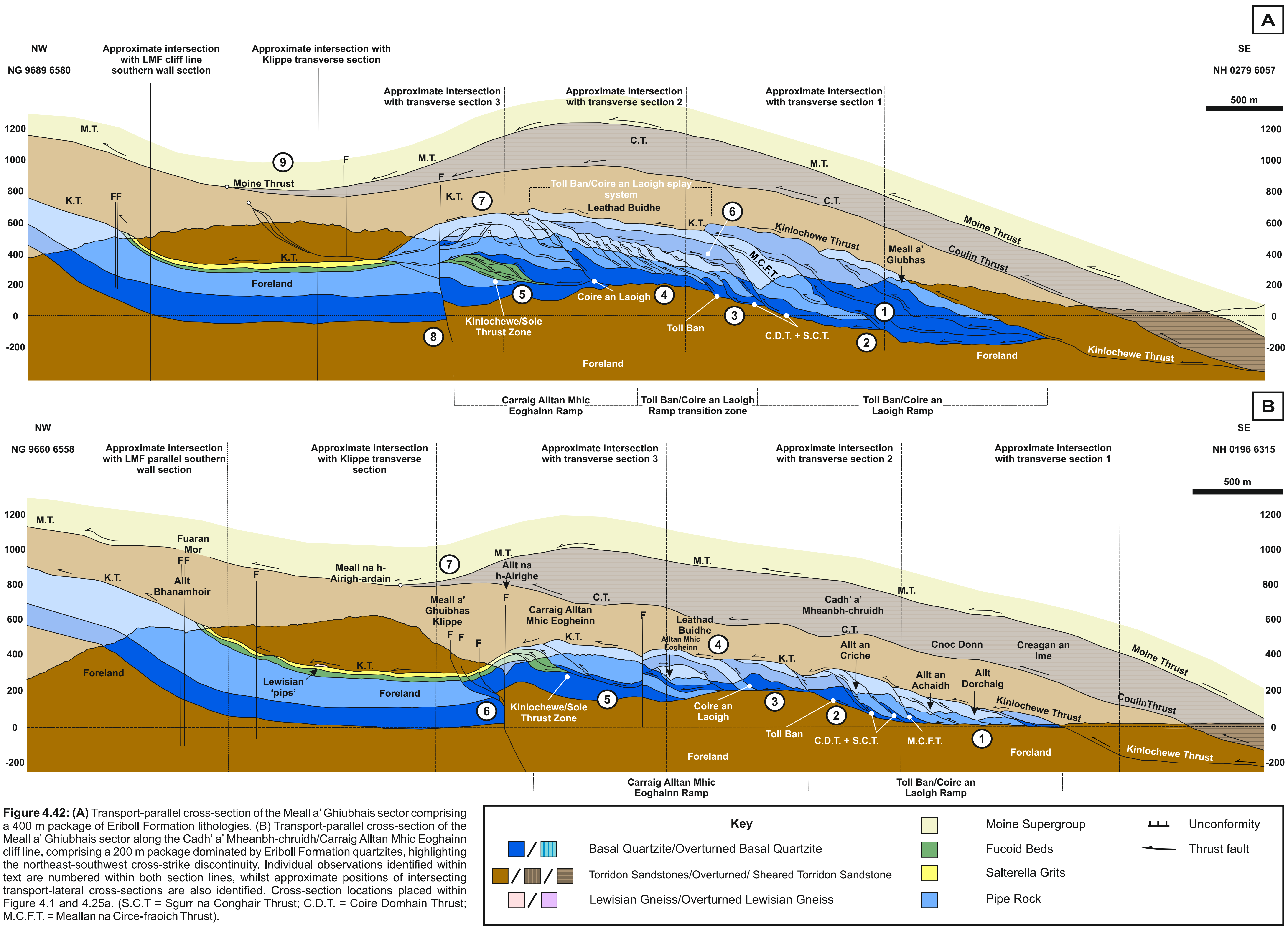


Figure 4.42: (A) Transport-parallel cross-section of the Meall a' Ghiubhais sector comprising a 400 m package of Eriboll Formation lithologies. (B) Transport-parallel cross-section of the Meall a' Ghiubhais sector along the Cadh' a' Mheanbh-chruidh/Carraig Alltan Mhic Eoghainn cliff line, comprising a 200 m package dominated by Eriboll Formation quartzites, highlighting the northeast-southwest cross-strike discontinuity. Individual observations identified within text are numbered within both section lines, whilst approximate positions of intersecting transport-lateral cross-sections are also identified. Cross-section locations placed within Figure 4.1 and 4.25a. (S.C.T = Sgurr na Conghair Thrust; C.D.T. = Coire Domhain Thrust; M.C.F.T. = Meallan na Circe-fraoich Thrust).

suggested to encourage such a geometrical development along-strike from the Leathad Buidhe Transverse Structure (LBTS), identified within the Meall a' Giubhas hillside (Figure 4.25b [2]; 4.42a [2]).

Northwards towards the Cadh' a' Mheanbh-chruidh cliff line, a drastic structural thinning is observed from this four hundred metre package dominated by Eriboll Formation Basal Quartzites and Pipe Rock units, to a series of two hundred metre structural packages dominated by Eriboll Formation (Pipe Rock) at Cnoc Donn [NH 0122 6334] (Figure 4.26b [4]; 4.42b [1]). This evidence supports the along-strike rise of décollement within this region. A further change in décollement level can be identified between the Beinn Eighe / Meall a' Ghiubhais transition zone and the Meall a' Ghiubhais sector along the Achnashellach Culmination Sole Thrust. Unlike the Beinn Eighe and Beinn Eighe / Meall a' Ghiubhais transition zones where two décollements were identified (Figure 4.24a [1]; 4.24b [1]), only one detachment is suggested within the Meall a' Ghiubhais sector; indicating a cross-strike change from a higher and lower detachment to one single detachment along the Torridonian sandstone / Eriboll Formation quartzite unconformity interface. As a result, no Torridonian sandstones are entrained within the Meall a' Ghiubhais thrust system (Figure 4.42a; 4.42b).

This along-strike change in décollement level is supported by field observations and fault network analyses within the Doire Dharaich hillside [NH 0023 6239 to NG 9968 6274], where pre-thrust folding illustrating north-south lateral shortening and ramp-on-ramp geometries are observed (Figure 4.25a [9]; 4.25b [2]). This suggests a deflection over a potential sub-décollement transverse structure, termed here the Doire Dharaich Transverse Structure (DDTS), linked to the Leathad Buidhe Transverse Structure (LBTS) along-strike (i.e., Leathad Buidhe / Doire Dharaich Transverse System). Deflection over this sub-décollement transverse structure is suggested to create a southward bifurcation into two décollements along-strike. Further support for these interpretations is identified along-strike in map-view within the Meallan na Circe-fraoich and Sgurr na Conghair thrusts where numerous bifurcations occur southward aligned sub-parallel to the regional (290 / 300°) transport direction (Figure 4.24b [5]; 4.25a [22]).

Forelandward of these structural packages, a distinct change in structural style is identified within map-view along the Leathad Buidhe viewpoint [NG 9948 6344], from thick thrust sheets to a defuse thrust imbricate zone; termed here the Toll Ban / Coire an Laoigh splay system (Figure 4.25a [2, 11]; 4.26b [5]). A northeast-southwest along-strike transition is identified. Toll Ban and Coire an Laoigh thrusts develop from a series of dominant, independent thrusts containing Torridonian sandstones and Eriboll Formation quartzites within the Beinn Eighe sector (Figure 4.24a [1, 2]), into a series of interconnecting thrusts (Figure 4.24b [1]; 4.25a [3, 10]); which develop northwards into a zone of shallow dipping imbricates indicating a 'thin flap' geometry over a one kilometre map-view length (Figure 4.42a [3, 4]). Along the Cadh' a' Mheanbh-chruidh cliff line however, the Toll Ban and Coire an Laoigh thrusts develop separately (Figure 4.42b [2, 3]), creating a broad five hundred metre ramp (i.e., Toll Ban / Coire an Laoigh Ramp; Figure 4.26b [1]; 4.42b [2. 3]). Within a three-dimensional context, these contrasting along-strike deformation style observations indicate oscillatory (i.e., forelandward-hinterlandward-forelandward) thrust propagation within the Meall a' Ghiubhais sector between the Toll Ban and Coire an Laoigh thrusts.

As the Toll Ban Thrust propagates forelandward, imbricates climb from Eriboll Formation Basal Quartzites to Pipe Rock Member lithologies (Figure 4.42a [3]). With continued propagation, displacement is transferred to the underlying Coire an Laoigh Thrust along the foreland Torridonian sandstone / Eriboll Formation (Basal Quartzite) interface (Figure 4.42a [4]). Synchronous thrust movements follow within both thrust systems as the Toll Ban / Coire an Laoigh splay system develops forelandward, with the majority of displacement focused along the Coire an Laoigh Thrust. Evidence to support synchronous thrusting can be observed within the Cadh' a' Mheanbh-chruidh cliff line in the form of large axial folds which develop between the Toll Ban and Coire an Laoigh thrusts (Figure 4.25a [1]; 4.26a [4]; 4.26b [7]).

Propagation within the Coire an Laoigh Thrust is suggested to then decrease as a result of interactions with the forelandward Carraig Alltan Mhic Eoghainn domain, resulting in footwall deformation along the Coire an Laoigh Thrust (Figure 4.30; 4.42a [5]); and a transfer of displacement hinterlandward back to the Toll Ban Thrust (Figure 4.42a [3]). Thrusting appears to then rapidly propagate forelandward along the Eriboll Formation (Pipe Rock) basal contact within the hanging-wall of the Coire an Laoigh Thrust (Figure 4.42a [4]). Propagation is assisted by interactions with overlying An t-Sron Formation (Fucoid Beds) which are observed to be smeared along the splay thrust planes; resulting in the production of very shallow stacked imbricates within map-view (Figure 4.25a [2, 11]; 4.28). This process bulges the structural package, further loading the underlying Coire an Laoigh Thrust. Movements along the Coire an Laoigh Thrust may still be observed but these are minimal in comparison to forelandward propagating thrusts within its hanging-wall (Figure 4.42a [4]).

As the Toll Ban / Coire an Laoigh ramp system locks up, a final hinterlandward phase of thrust propagation truncates the tops of these shallow imbricates, placing thicker thrust sheets of the Cadh' a' Mheanbh-chruidh domain hinterland on top (Figure 4.42a [6]). Evidence to support these observations are identified along the Cadh' a' Mheanbh-chruidh cliff line where hanging-wall Eriboll Formation (Basal Quartzites) are truncated by later thrusts which indicate breaching, out-of-sequence thrusting placing Eriboll Formation Pipe Rock on top of Basal Quartzite units (Figure 4.26b [6, 14]).

Along the Toll Ban / Coire an Laoigh Ramp front, a large zone of deformation supporting oscillating thrusting can be identified within the Alltan Mhic Eoghainn cliff line (i.e., the Alltan Mhic Eogh syncline; Figure 4.25a [12]; 4.26b [8]). Within this zone, forelandward propagation of the Toll Ban / Coire an Laoigh Ramp creates a major syncline within its footwall. The Alltan Mhic Eogh syncline is then subsequently thrusted and then refolded creating a plunging thrust lense in map-view, during oscillatory thrust processes (Figure 4.42b [4]). Evidence within foreland successions beneath this structure indicate gently folded successions (Figure 4.26b [9]), suggesting down-cutting towards the foreland along the Sole Thrust; either as a result of thrust propagation over a small Torridonian sandstone-dominant fault block, frontal loading from the Toll Ban / Coire an Laoigh Ramp on the underlying Carraig Alltan Mhic Eoghainn Ramp sequence, and / or the forelandward development of the Carraig Alltan Mhic Eoghainn Ramp (Figure 4.26b [13]; 4.42b [4]).

Along the Carraig Alltan Mhic Eoghainn cliff line, the Sole Thrust is observed climbing the hillside into An t-Sron Formation imbricates (Figure 4.26b [2]; 4.35; 4.42b [5]). Hanging-wall Eriboll Formation (Pipe Rock) units within this sequence carry large east-west to north-south orientated antiforms (Figure 4.33a), a suggested by-product of interactions between the climbing Sole Thrust and down-cutting Kinlochewe roof-thrust which deforms lithologies within its footwall. Evidence supporting these observations are identified within the foreland of the Carraig Alltan Mhic Eoghainn domain / ramp, in front of the Meall a' Ghiubhais Klippe, where a five hundred metres zone of heavily fractured, Eriboll

Formation (Pipe Rock) dominant, units are identified within map-view indicating the Kinlochewe / Sole Thrust interaction zone (Figure 4.42a [5]).

Within this region, footwall splays off the down-cutting Kinlochewe Thrust are viewed creating structures such as the Bhanabhaig Klippe (Figure 4.26b [10]; 4.42a [7]), whilst the Sole Thrust is suggested to be within Eriboll Formation (Basal Quartzites) and An t-Sron Formation lithologies (Figure 4.42a [5]). These observations support field evidence which suggests an out-of-sequence last phase of loading and down-cutting by the Kinlochewe Thrust as it descends into foreland lithologies producing the Bhanabhaig Klippe within its footwall, and the Meall a' Ghiubhais Klippe within its hanging-wall.

South-westwards along-strike, the Sole Thrust indicates a thickening / bulging of An t-Sron Formation lithologies from the imbricate splay on the Carraig Alltan Mhic Eoghainn cliff line (Figure 4.42b [5]) to a two hundred to three hundred metre thick series of imbricated An t-Sron Formation lithologies along the south-western edge of the Meall a' Ghiubhais Klippe (Figure 4.24b [6]). This along-strike thickening / bulging could be in response to differential interactions within the pre-thrust template (i.e., height of steps relative to thrust level). The Sole Thrust continues south-westwards into the Au Ruadh-stac Beag hillside within two dominant thrusts (Figure 4.25a [6]). Map-view observations within this region are aligned sub-parallel to discontinuities identified hinterlandward within the Carraig Alltan Mhic Eoghainn and Cadh' a' Mheanbh-chruidh domains, as well as, differential thrusting along the overlying Kinlochewe roof-thrust, which within this region is observed two hundred metres higher than on the north-eastern side of the Klippe (Figure 4.25a [5, 2, 9, 22]; 4.25b [2, 3, 7, 8]; 4.39b; 4.39c). These transport sub-parallel discontinuities indicate potential interactions with small frontal steps and / or deflections over sub-décollement transverse structures continuing forelandward from the Doire Dharaich hillside (i.e., Leathad Buidhe Transverse Structure).

Within the Kinlochewe / Sole Thrust interaction zone, a series of large vertical dextral faults slice the front of the Meall a' Ghiubhais Klippe (i.e., the Allt na h-Alrighe / Cnoc na Gaoithe fault system; Figure 4.25a [19]; 4.36). These faults which branch off a main dominant fault within the Cnoc na Gaoithe gorge indicate a splay system (Figure 4.42b [6]), which could potentially be a proto-ramp which failed to develop as a result of the interaction between the down-cutting of the Kinlochewe roof thrust and the rising Sole Thrust. These observations are supported by weakly folded foreland successions within the Cnoc na Gaoithe region which could potentially resemble a subsurface propagating blind thrust (Figure 4.25a [13] 4.26b [9]).

Forelandward rise of the Sole Thrust from Eriboll Formation (Pipe Rock) lithologies to An t-Sron Formation units may also indicate a potential step within the foreland which the sequence is trying to overcome (i.e., the plinth along which the Meall a' Ghiubhais Klippe now resides; Figure 4.24b [6]; 4.42a [8]; 4.42b [6]). The roof-sequence comprising the Kinlochewe Thrust responses to this forelandward step by down-cutting into its footwall, a process which is also observed along-strike within the overlying Coulin Thrust. The Coulin Thrust Sheet is itself down-cut by later movements along the Moine Thrust as no evidence for the Coulin Thrust Sheet is observed within the Meall a' Ghiubhais Klippe sequence or within the foreland (Figure 4.42a [9]; 4.42b [7]).

4.4.2.5. Meall a' Ghiubhais Sector: Summary

Within the Meall a' Ghiubhais Sector, fault network analyses and field observations allow the following pertinent characteristics to be identified within Table 4.2. Along-strike observations within the Beinn Eighe to Meall a' Ghiubhais sectors indicate a series of cross-strike discontinuities within the Loch Maree Transverse Zone southern wall, indicating an along-strike thinning of structural packages towards the Loch Maree Fault.

4.5. Summary

A series of cross-strike discontinuities are identified within the Beinn Eighe and Meall a' Ghiubhais sectors which comprise the Loch Maree Transverse Zone southern wall (Table 4.1; 4.2). Cross-strike discontinuity observations within the southern wall are discussed in greater detail in chapter five, in context with observations identified within the Loch Maree Transverse Zone northern wall (Heights of Kinlochewe Sector), to establish cross-strike linkages within the Loch Maree Transverse Zone.

Meall a' Ghiubhais Sector: Summary findings	
Region	**Observation highlights**
Cadh' a' Mheanbh-chruidh domain: **Toll Ban/Coire an Laoigh Ramp**	• Broad hinterland thrust sheets (200-400 m) of Eriboll Formation (Pipe Rock). Only a few dominant thrusts (i.e., Meallan an Circe-fraoith Thrust). Thrusts place Pipe Rock-onto Pipe Rock (flat-on-flat geometries) within a regional (290 / 300°) transport direction. Shallow-dipping lithologies observed (20-30°) until thrust map-traces approached leading to steeper hanging-wall anticline units (50-70°). • System develops northwards from these 400 m sequences into 200 m 'flap-like' structural packages along the Cadh' a' Mheanbh-chruidh cliff line. Sole Thrust is observed placing Eriboll Formation lithologies onto undeformed Torridonian sandstone foreland. No Torridonian sandstones entrained within imbricate system. • Ramp-on-ramp geometries identified along the Doire Dharaich hillside indicating a bulging of the forelandmost portions of the Cadh' a ' Mheanbh-chruidh domain and elements of pre-thrust folding. Identification of potential sub-decollement transverse structure (Doire Dharaich Transverse Structure) sub-parallel to regional transport and the Loch Maree Fault (LMF). Ramp-on-ramp geometries not continuous into Carraig Alltan Mhic Eoghainn domain. • Forelandmost sections of the domain indicate a series of thin imbricate splays displaying lateral (N-S) shortening which have been bulged (i.e., Toll Ban / Coire an Laoigh splay system). Along the Cadh' a' Mheanbh-chruidh hillside these splays develop into a dominant ramp creating large hanging-wall anticlines and deformation within its footwall (i.e., Toll Ban / Coire an Laoigh Ramp). Thin imbricates indicate oscillatory thrusting, shallow stacking and interactions with overlying An t-Sron Formation lithologies which are smeared along splay thrust planes.
Carraig Alltan Mhic Eoghainn domain: **Carraig Alltan Mhic Eoghainn Ramp**	• Very shallow dipping (10-30°) imbricates comprising Eriboll Formation (Pipe Rock) observed. Imbricate stacking occurs as a result of layer-parallel shear and layer-parallel shortening, *Monocraterion* and *Skolithos* 'pipes' indicate very little internal deformation or strain within thrust imbricates. Broad open folds also identified within Creagan Ruadh developing north-eastwards towards the Loch Maree Fault into tight folds with varying axial traces within Loch Allt an Daraich region. Increase deformation therefore observed towards the Loch Maree Fault. • Broad (325 m) syncline and thrust lense identified within footwall of Toll Ban / Coire an Laoigh Ramp. Along the Carraig Alltan Mhic Eoghainn cliff line, large east-west to north-south orientated antforms associated within the development of this structure and interactions with Kinlochewe roof-thrust identified. Structures linked to a 500 m zone of heavily fractured Eriboll Formation quartzites which indicate out-of-sequence thrusting and footwall interactions of down-cutting Kinlochewe roof-thrust (i.e., Bhanabhaig Klippe). Sequence cut by later dextral faults. • At Carraig Alltan Mhic Eoghainn cliff line base, Sole Thrust observed cutting up cliff line from Eriboll Formation (Pipe Rock) quartzites into An t-Sron Formation lithologies, carrying observed large Eriboll Formation antiforms within its hanging-wall. Lower slopes beneath Sole Thrust weakly folded but otherwise undisturbed foreland succession of Torridonian sandstones and Eriboll Formation quartzites. Broad NE-SW trending warps suggest a potential blind basal thrust (i.e., new proto-ramp which failed to develop) within vertical fault system at Cnoc na Gaoithe.
Meall a' Ghiubhais Sector: **Cross-strike discontinuities**	• Two senses of cross-strike discontinuity observed: (1) Northeast-southwest: Drastic north-eastwards reduction from 800 m structural packages containing Torridonian sandstones and Eriboll Formation quartzites to 200 m Eriboll Formation structural packages along the Cadh' a' Mheanbh-chruidh/ Carraig Alltan Mhic Eoghainn cliff line. Transverse structure observed along the Doire Dharaich hillside (i.e., Doire Dharaich Transverse Structure [DDTS]) linked to those observed within Leathad Buidhe (i.e., Leathad Buidhe Transverse Structure [LBTS]). Along-strike changes in detachment also observed. (2) Northwest-southeast: Transport-parallel structural style change identified between two domains. Result of along-strike Toll Ban/Coire an Laoigh thrust system developments, oscillatory thrusting and development of two dominant ramp sequences. Interactions of rising Sole Thrust and down-cutting Kinlochewe roof-thrust also lead to forelandward discontinuities (i.e., 500 m deformation zone/Bhanabhaig Klippe) as a result of out-of-sequence thrusting and downwarping / loading of the deformation front at the Meall a' Ghiubhais Klippe.

Table 4.2: Summary findings within the Meall a' Ghiubhais Sector. Observation highlights within Cadh' a' Mheanbh-chruidh and Carraig Alltan Mhic Eoghainn domains identified, whilst cross-strike discontinuities also summarised.

Chapter Five:

Identification and analysis of Transverse Zones in Thrust Belts: Kinematic Partition across the Loch Maree Transverse Zone (northern wall), Moine Thrust Belt, Scotland

Chapter five serves to illustrate the findings undertaken as part of the remapping of the Kinlochewe region along the Loch Maree Fault northern wall within the Moine Thrust Belt, NW Highlands, Scotland. Emphasis is placed on the validation of new methodologies applied to identify transverse structures and cross-strike linkages within transverse zones. Results serve to define the kinematic evolution of the Loch Maree Transverse Zone (LMTZ), to differentiate lateral discontinuities that arise syn-kinematically during thrusting and pre-thrust discontinuities, and to provide insight into processes by which thrust-belt transverse zones may originate and evolve.

5.1. Thrust architecture north of Loch Maree Transverse Zone: Heights of Kinlochewe Sector (Northern Loch Maree Fault Sidewall)

The northern sidewall of the Loch Maree Transverse Zone (LMTZ) and Loch Maree Fault (LMF) is dominated by a number of right-way-up and overturned thrust sheets (i.e., Coire Each, Meallan Ghobhar and Heights of Kinlochewe) comprising the Heights of Kinlochewe sector (Figure 5.1a; 5.2a; 5.2b). The Coire Each Thrust Sheet is dominated by right-way-up Eriboll and An t-Sron Formation units (Figure 5.1a [1]) which are structurally overlain by the Meallan Ghobhar Thrust Sheet, characterised by overturned Lewisian gneisses, Torridonian sandstones and Eriboll Formation quartzites (Figure 5.1a [2]). Coire Each Thrust acts as the regional Sole Thrust within the northern wall of the Heights of Kinlochewe sector (Figure 5.1a [3]). The Meallan Ghobhar overturned Thrust Sheet is structurally overlain by the Heights of Kinlochewe Thrust Sheet carrying undeformed

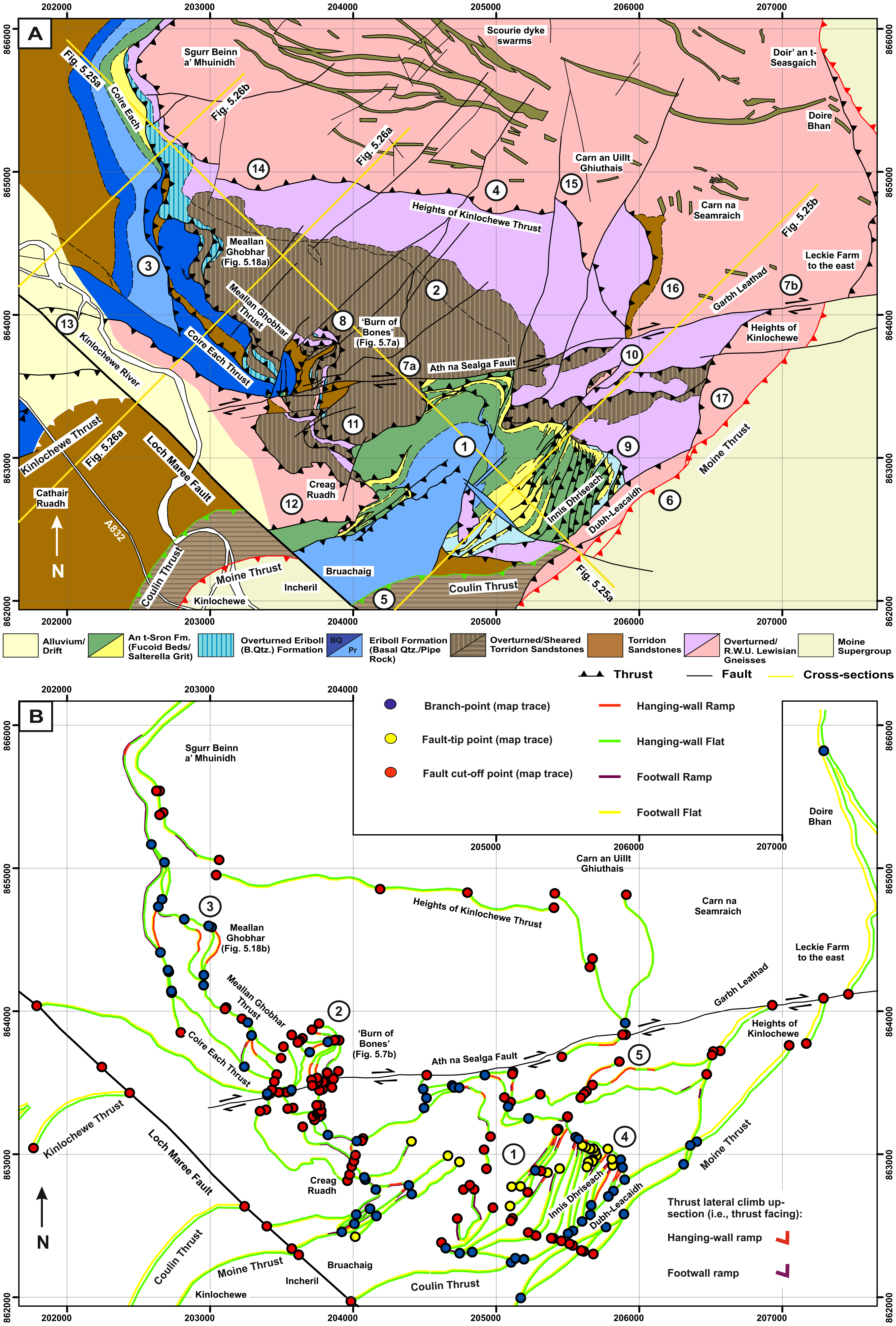


Figure 5.1: (A) Geological map of the Heights of Kinlochewe sector, comprising the northern wall of the Loch Maree Transverse Zone and Loch Maree Fault. Northern wall is composed of the Coire Each, Meallan Ghobhar and Heights of Kinlochewe thrust sheets. Observations highlighted within the text are numbered. **(B)** Fault network analysis of the Heights of Kinlochewe sector. Three domains are identified based on thrust ramp analyses: (1) Glen Bruachaig-Incheril Window, (2) 'Burn of Bones' domain and (3) Meallan Ghobhar domain. Observations highlighted within the text are numbered.

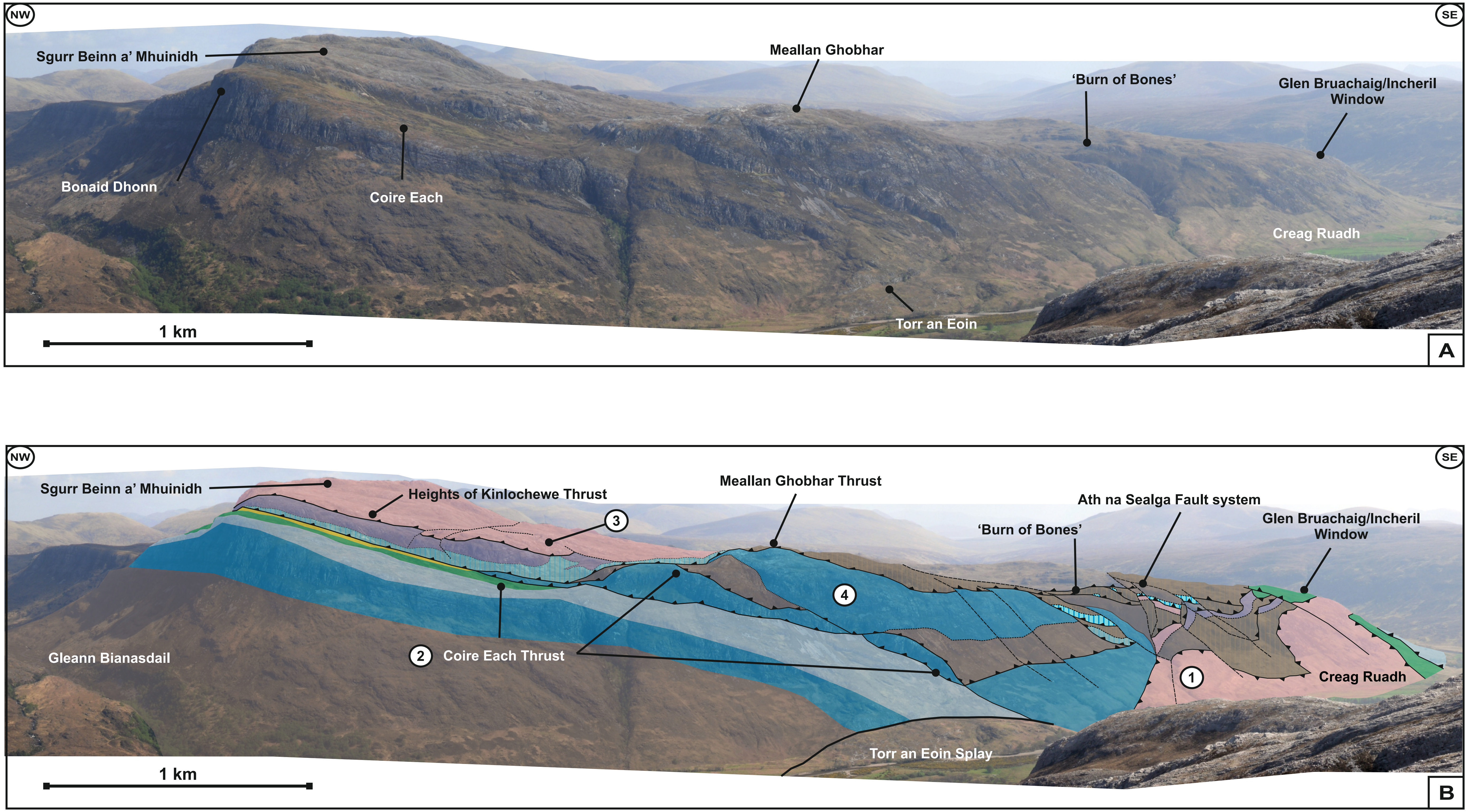
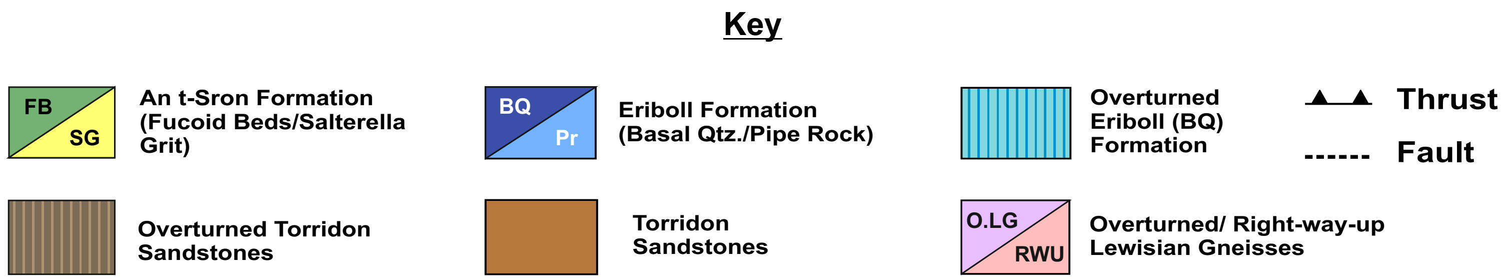


Figure 5.2: (A) Overview of the northern wall of the Loch Maree Fault (LMF), comprising the Heights of Kinlochewe Sector (northern wall of the Loch Maree Transverse Zone [LMTZ]).

(B) Geological overlay highlighting complex along-strike thrust geometries between the Coire Each, Meallan Ghobhar and Heights of Kinlochewe. Interactions of the Loch Maree Fault system at Torr an Eoin, Ath na Sealga dextral fault and Glen Bruachaig/Incheril Window are also identified. Observations highlighted in the text numbered.



Lewisian gneisses containing Scourie dykes trending northwest-southwest, parallel to those in the foreland Lewisian basement (Figure 5.1a [4]). These thrust sheets are overridden by the Coulin and Moine thrust sheets (Figure 5.1a [5, 6]).

Few thrust ramps are identified within the northern wall of the Loch Maree Fault. Thrust ramp fault network analyses can however identify three structural domains within the Heights of Kinlochewe sector (Figure 5.1b [1, 2, 3]):

- <u>Glen Bruachaig-Incheril Window domain:</u> Dominated by the Glen Bruachaig-Incheril Window within the Abhainn Bruachaig valley [NH 0541 6239], comprising the hillsides of Innis Dhriseach [NH 0536 6286], Torran nan Teud [NH 0479 6257] and Creag Ruadh [NH 0366 6266] (Figure 5.1a [1]; 5.1b [1]). Domain bound on its north-eastern edge by the dextral Ath na Sealga Fault; laterally truncating lithologies westward up to and including the Moine Thrust (Figure 5.1a [7]).

- <u>'Burn of Bones' domain:</u> Confined to the 'Burn of Bones' valley and hillside sequence [NH 0365 6368], through which the Allt Chnàimhean river and Ath na Sealga fault system cuts (Figure 5.1a [7, 8]; 5.1b [2]; 5.2b [1]). Sequence allows a three-dimensional view to be determined within the transport direction from the Loch Maree valley floor to the hillside top.

- <u>Meallan Ghobhar domain:</u> Sequence forelandward from the 'Burn of Bones' towards the Meallan Ghobhar [NH 0290 6454] and Coire Each hillsides [NH 0242 6549]. Domain indicates interactions between the Coire Each and Meallan Ghobhar thrust sheets (Figure 5.1a [3]; 5.2b [2]) and the development of the Heights of Kinlochewe Thrust Sheet (Figure 5.1a [4]; 5.2b [3]).

5.1.1. Glen Bruachaig-Incheril Window domain

Thrust imbricates within the Glen Bruachaig-Incheril Window [NH 0491 6295] are dominated by Lower Palaeozoic An t-Sron Formation (Fucoid Bed and Salterella Grit) units (Figure 5.3a; 5.3b). Units dip steeply (60 to 70° SE) within the Window hinterland, through near vertical within central Salterella Grit sections of the Window (85°; Figure 5.3b); to shallow dipping (20 to 35° NW) within the Window foreland indicating a domed / bulged duplex with an Eriboll Formation (Pipe Rock) core (Figure 5.1a [1]; 5.3; 5.4). Imbricates develop within the Coire Each Thrust Sheet, within the footwall of the overlying Meallan Ghobhar Thrust and respective overturned thrust sheet which acts as its roof-thrust.

The relationship between the Meallan Ghobhar Thrust and its footwall is complex and cannot be explained by simple duplex formation (e.g., Boyer & Elliott, 1982). Thrust imbricates within the Coire Each Thrust Sheet are observed stratigraphically cutting up-section north-eastwards from An t-Sron Formation Fucoid Beds and Salterella Grits within the south-western portions of the window into Durness Group (Ghrudaidh Formation) limestones [NH 0573 6299] (Figure 5.1a [9]). These observations support thrust ramp nucleations identified within the fault network analyses along the north-eastern termination of the Glen Bruachaig / Incheril Window (Figure 5.1b [4]). Overlying Meallan Ghobhar Thrust truncates the Window along this termination, whilst also cutting stratigraphically up- and down-section within its footwall leading to the generation of numerous fault-tip points within map-view (Figure 5.1a [9]; 5.1b [4]).

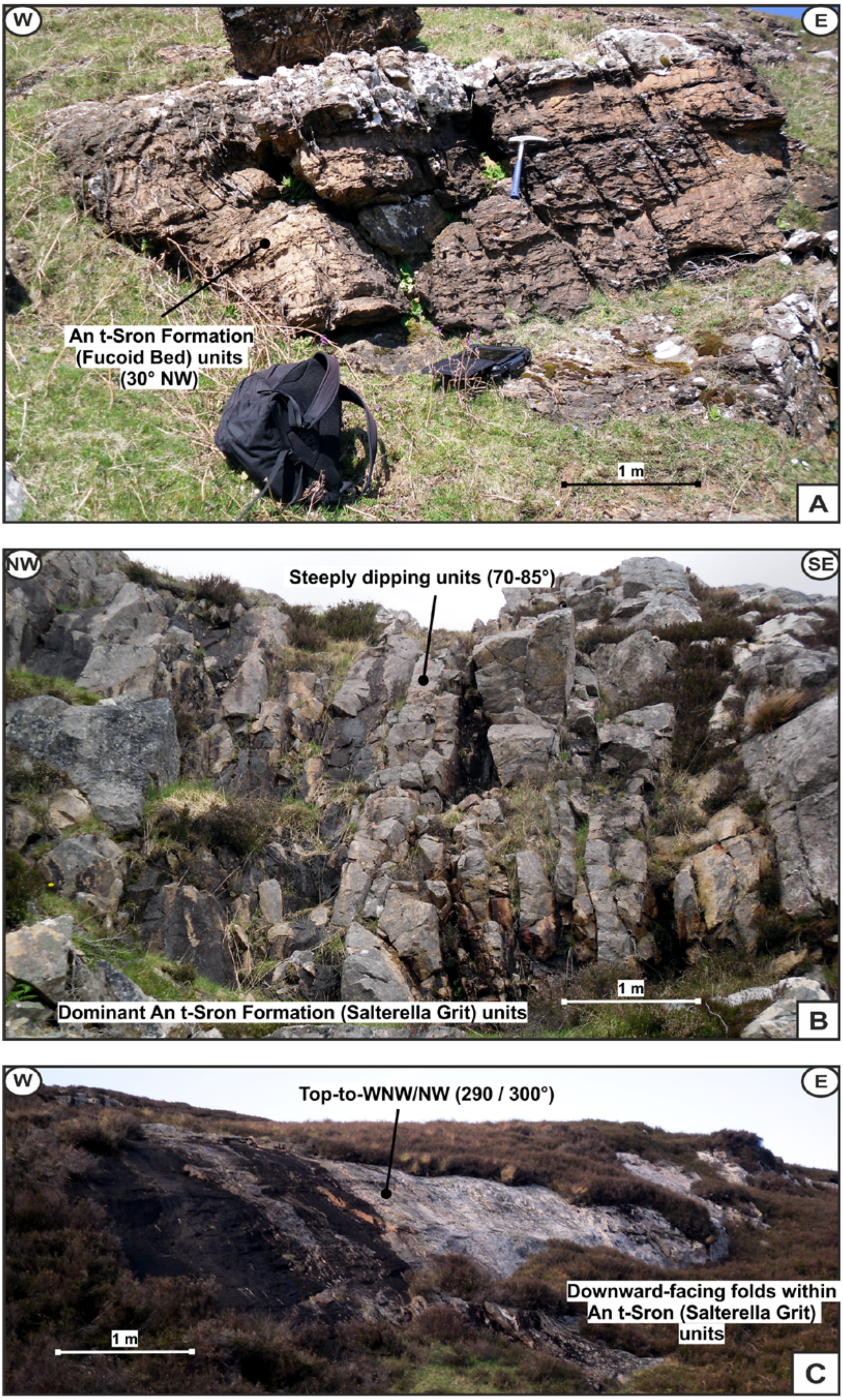


Figure 5.3: (A) Shallow (30° NW) dipping An t-Sron Formation (Fucoid Beds) within the north-western sections of the Glen Bruachaig-Incheril Window. **(B)** Vertical to near vertical (70-85°) An t-Sron Formation (Salterella Grits) within the central Salterella Grit dominant sections of the Window. **(C)** Downward-facing folds within An t-Sron Formation (Salterella Grit) units. Evidence supports a duplex which has been internally bulged during its development within a regional (i.e., 290 / 300°) WNW/NW-vergent thrust system.

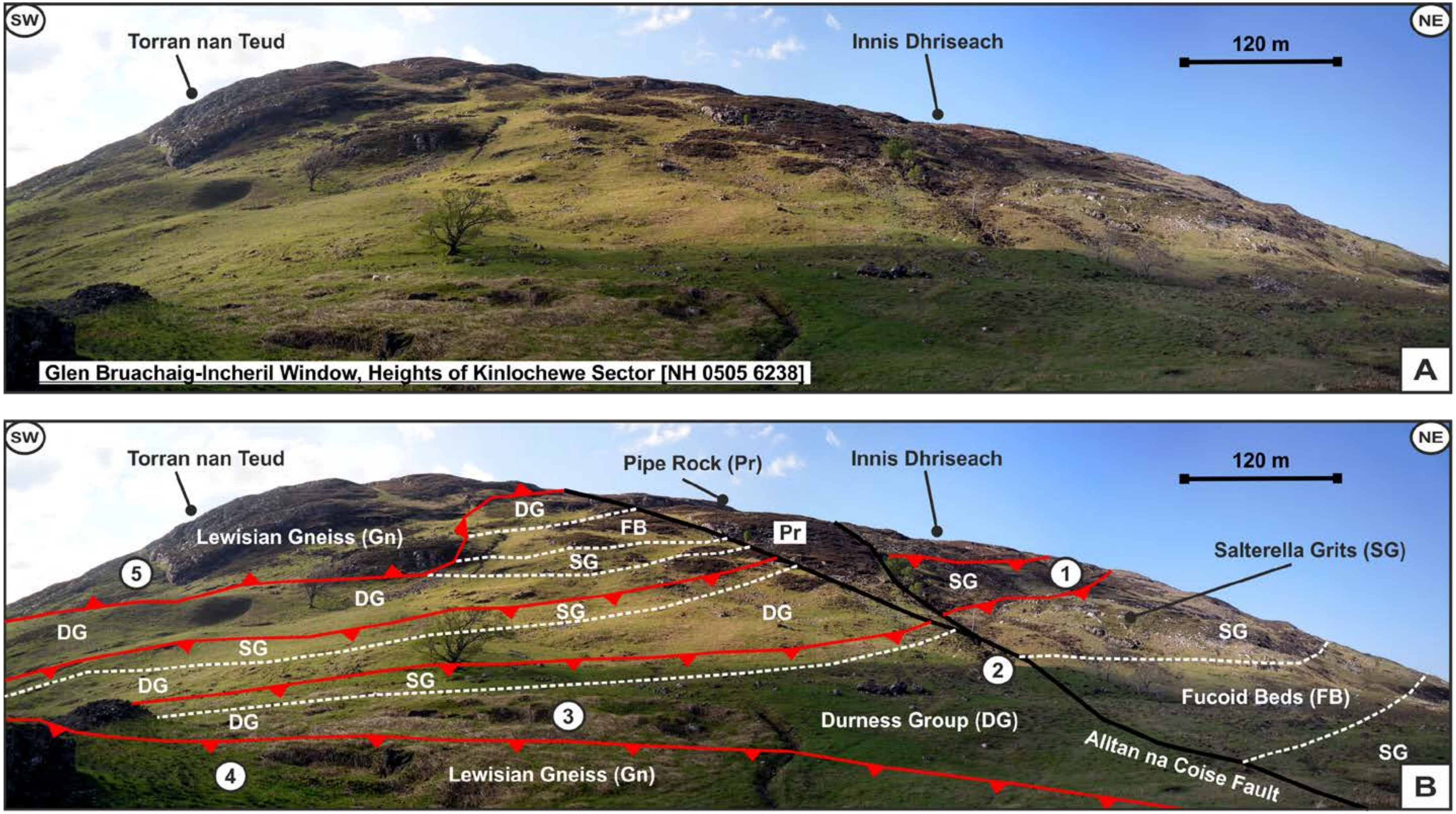


Figure 5.4: (A) Glen Bruachaig-Incheril Window (facing NW) towards the core of the Window along the Torran nan Teud [NH 0479 6257] and Innis Dhriseach [NH 0536 6286] hillsides. **(B)** Structural overlay illustrating the cross-strike and along-strike distribution of thrust imbricates within the south-western portions of the Glen Bruachaig-Incheril Window. Northeastern sections are dominated by thrust imbricates rising north-eastwards from Salterella Grits to Durness Group limestones, whilst southwestern sections preserve Durness Group (Ghrudaidh Formation) limestones. Result of NW-SE orientated vertical Alltan na Coise Fault dropping western side. Observations highlighted in text numbered.

Western portions of the Window show no such truncation, with footwall gliding at the top of the more competent An t-Sron Formation (Salterella Grit) units creating downward-facing folds (Figure 5.3c; 5.4b [1]); indicating a top-to-west-northwest to northwest (290 / 300°) transport within hinterland sections of the Heights of Kinlochewe sector / Loch Maree Fault northern wall. The Window is itself truncated by a northwest to southeast orientated vertical dextral fault (Alltan na Coise Fault [NH 0512 6252]) entraining Eriboll Formation (Pipe Rock) units from the Window core. This fault drops the western side of the Glen Bruachaig-Incheril Window, preserving Durness Group limestones (Figure 5.4 [2, 3]).

Within the Glen Bruachaig-Incheril Window hinterland and along the south-eastern side of the Abhainn Bruachaig valley [NH 0541 6239] higher thrust sheets are identified (Figure 5.4b [4, 5]). Gneisses within the Abhainn Bruachaig valley on the south-eastern side of the Window comprise the higher Heights of Kinlochewe Thrust Sheet, along with the small klippe (of gneiss) north of Torran nan Teud [NH 0479 6257] (Figure 5.4b [5]). At Allt Dubh-Leacaidh [NH 0589 6255], the Moine Thrust (*senso stricto*) within the south-eastern wall of the Abhainn Bruachaig valley cuts down to rest on more massive gneisses belonging to the Heights of Kinlochewe Thrust Sheet (Figure 5.1a [6]).

Along the western edge of the Glen Bruachaig-Incheril Window, nearest the Loch Maree Fault, thrust sheets comprising undeformed Torridonian sandstones and foliated, sheared metasandstones are identified (Heights of Kinlochewe and Coulin respectively [NH 0473 6217]; Figure 5.1a [5]). Observations indicate that the Coulin Thrust Sheet overlies the massive gneisses and Torridonian sandstones of the Heights of Kinlochewe Thrust Sheet. These structurally higher thrust sheets are not identified within the north-eastern sections of the Glen Bruachaig-Incheril domain, suggesting that they are cut off against the top sections of the Window; supporting later truncations within the development of the imbricate system. Conversely, along the higher thrust sheets to the northeast of the Window domain, overturned units of Lewisian gneisses and Torridonian sandstones comprising the Meallan Ghobhar Thrust Sheet are identified [NH 0570 6349] (Figure 5.1a [10]). As such a northeast-southwest cross-strike discontinuity within the Glen Bruachaig-Incheril Window domain is identified. Within these overturned sequences, overturned unconformities and thrust splays interact creating complex structural geometries, highlighted by thrust ramps within map-view fault network analyses (Figure 5.1a [10]; 5.1b [5]; 5.5a).

Along the higher hinterland sections of the Heights of Kinlochewe sector, the Glen Bruachaig-Incheril Window domain is confined by a large dextral fault (i.e., Ath na Sealga Fault). The Ath na Sealga Fault truncates the northern portions of the Window and the Meallan Ghobhar Thrust Sheet to the southwest [NH 0477 6355], indicating a later movement phase than the Window development (Figure 5.1a [7a, 7b]). This large dextral fault, not previously identified within the thrust sequence, continues west-northwest to east-northeast across Garbh Leathad displacing the overlying Heights of Kinlochewe and Moine thrust sheets by c. 2.8 kilometres [NH 0714 6407] (Figure 5.1a [7b]). Foliated, sheared metasandstones of the Coulin Thrust Sheet reappear north of the Ath na Sealga Fault in the footwall of the dextrally displaced Moine Thrust.

Further supportive evidence is found east of the Leckie Farm [NH 0968 6451], where mylonitic Moine psammites are structurally placed over mylonitic sheared metasandstones of the Coulin Thrust Sheet (Leslie, pers. comms. 2011). Within the confines of the Glen Bruachaig-Incheril Window domain however, this large dextral fault is difficult to observe due to the fissile nature of the An t-Sron Formation. Both the Ath na

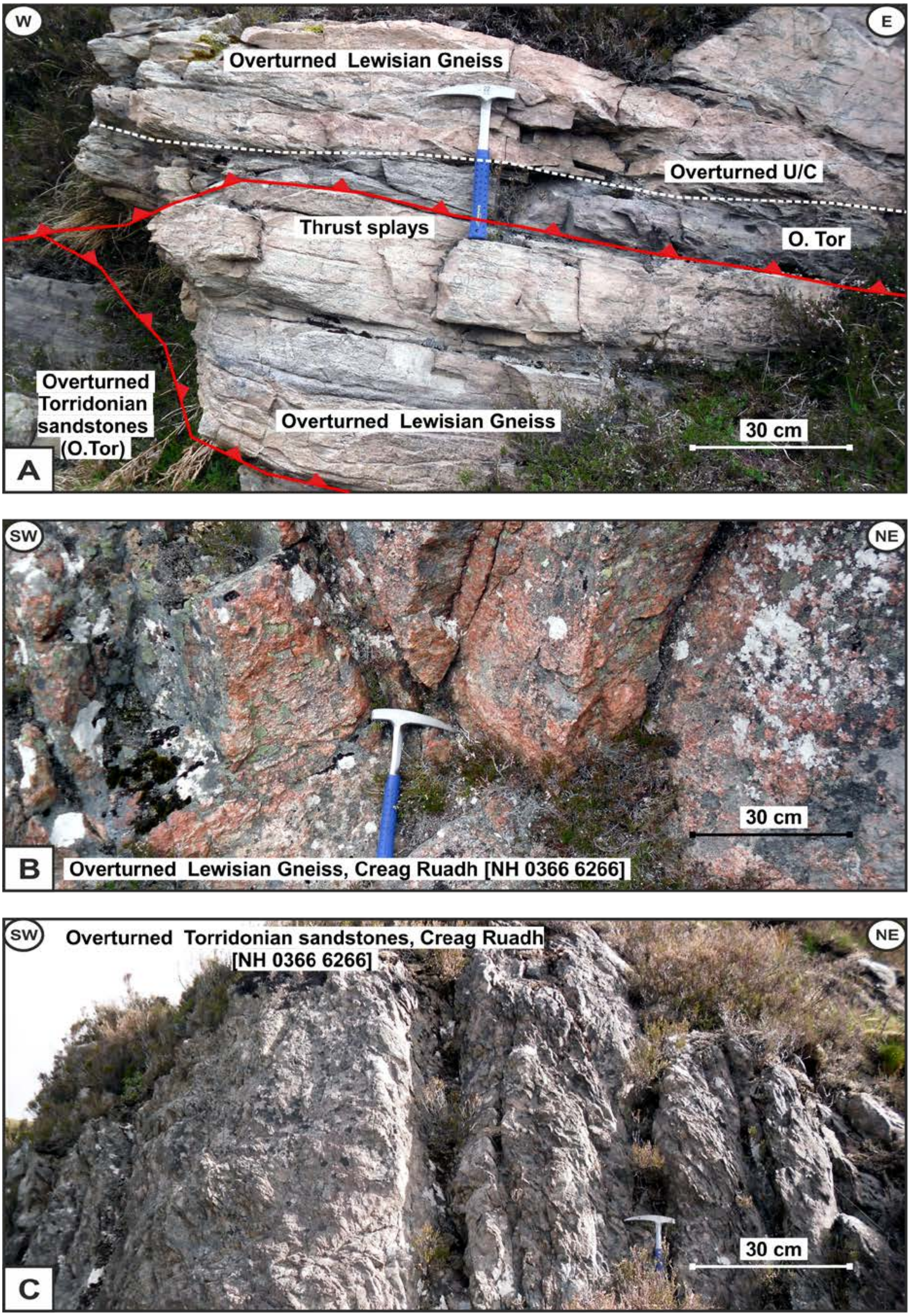


Figure 5.5: (A) Complex geometries identified between thrust splays and overturned unconformities within the Meallan Ghobhar thrust sheet. **(B)** Overturned Lewisian gneisses which appear 'sweated' near overlying thrust interactions. **(C)** Overturned Torridonian sandstones which appear heavily brecciated. Southwesterly-dipping units vary from 30° to near vertical.

Sealga and Alltan na Coise faults displace Moine Supergroup lithologies indicating that strike-slip movements occur as one of the last phases of movement within the northern wall of the Loch Maree Transverse Zone.

Within the foreland of the Glen Bruachaig-Incheril Window along the Creag Ruadh hillside, interactions between the Window and the overlying overturned Lewisian gneisses and Torridonian sandstones of the Meallan Ghobhar Thrust Sheet, which dominate the forelandward domains of the Heights of Kinlochewe, are observed (Figure 5.1a [11]; 5.5b; 5.5c). Lewisian gneisses within the Meallan Ghobhar Thrust Sheet differ in nature to the overlying right-way-up Heights of Kinlochewe gneisses, appearing 'sweated' (i.e., indicate a change of mineralogy proportions during deformation; Hutton (1946)), whilst containing no Scourie dyke swarms (Figure 5.5b).

Evidence supporting the overturned nature of these units is observed within the north-western corner of the Glen Bruachaig-Incheril Window [NH 0393 6306], where interactions of gneisses on top of Torridonian sandstones are identified; indicating an overturned unconformity (Figure 5.6a). No evidence of thrusting is present within this outcrop; however underlying and overlying thrusts are identified ten metres above and below indicating imbrication within the overturned units along the top of the Heights of Kinlochewe cliff line (Figure 5.1a [11]). Overturned Torridonian sandstones along the Heights of Kinlochewe cliff line indicate a forelandward steepening of southwest-dipping units from 30° to 80° from Creag Ruadh to the 'Burn of Bones' valley within the west-northwest to northwest-vergent (i.e., 290 / 300°) thrust system (Figure 5.5c), suggesting a system undergoing transpressional deformation during forelandward development.

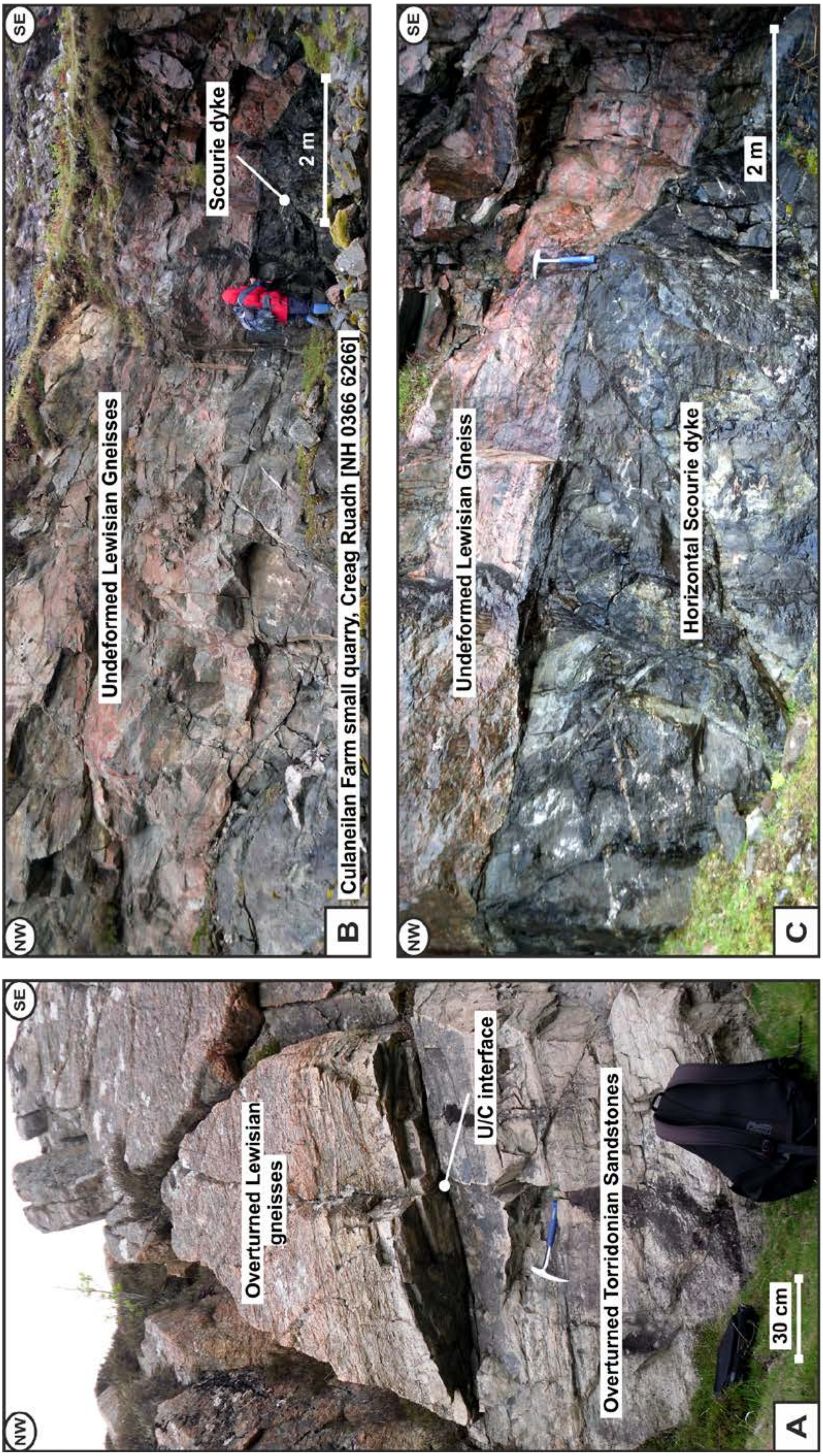


Figure 5.6: (A) Overturned unconformity within the Creag Ruadh hillside [NH 0393 6306], comprising overturned Torridonian sandstones overlain by overturned Lewisian gneisses. **(B)** Small quarry at the base of Creag Ruadh, near the Culaneilan Farm [NH 0366 6266] within which horizontally orientated Scourie dykes are observed **(C)**. Evidence indicates that these units link with the overlying right-way-up Lewisian gneisses of the Heights of Kinlochewe thrust sheet along a southwest-dipping thrust which can be mapped for c. 2 km. Down-warping of higher thrust sheets along a sidewall is therefore suggested along the northern wall of the Loch Maree Fault (i.e., Creag Ruadh Sidewall).

Along the base of the Glen Bruachaig-Incheril Window cliff line, a small quarry identifies a slab of southwest-dipping undeformed gneisses containing Scourie dykes orientated horizontal to the cliff line at Creag Ruadh near the Culaneilan Farm [NH 0366 6266] (Figure 5.1a [12]; 5.6b; 5.6c). Scourie dyke containing gneisses lie on a southwest-dipping thrust [NH 0391 6281] which can be traced from the northwest boundary of the Glen Bruachaig-Incheril Window northwest for c. 2 kilometres until it is truncated against the Loch Maree Fault within the Kinlochewe River [NH 0178 6403] (Figure 5.1a [13]). Units comprise the overlying Heights of Kinlochewe Thrust Sheet, here lying on a sidewall orientated sub-parallel to the Loch Maree Fault (i.e., Creag Ruadh Sidewall), which overlies the overturned Meallan Ghobhar Thrust Sheet and the An t-Sron Formation imbricates of the Glen Bruachaig-Incheril Window. Observations indicate a down-warping of the Heights of Kinlochewe Thrust Sheet against the Loch Maree Fault.

5.1.2. 'Burn of Bones' domain

The 'Burn of Bones' domain is composed of an eight hundred metre long river-cutting (Allt Chnàimhean) through the Heights of Kinlochewe sector (NH 0343 6336; Figure 5.2b [1]; 5.7a; 5.8a). Within the lower slopes of the Heights of Kinlochewe and the 'Burn of Bones' sidewalls, complex thrust geometries are observed (Figure 5.8b). Complex thrust geometries occur as a result of rheological and structural interactions of the Coire Each, Meallan Ghobhar and Heights of Kinlochewe thrusts sheets, together with the Ath na Sealga dextral fault system (Figure 5.7a; 5.8b). Fault network analyses highlight this structural combination of complexities, which result in a dominance of fault cut-off points within map-view in this domain (Figure 5.7b [1]). Fault cut-off analyses indicate a domain dominated by brittle fault tectonics rather than ductile processes. Observations are supported by large numbers of fault systems entering the 'Burn of Bones' domain from the Heights of Kinlochewe central sector [NH 0439 6422], including the Ath na Sealga

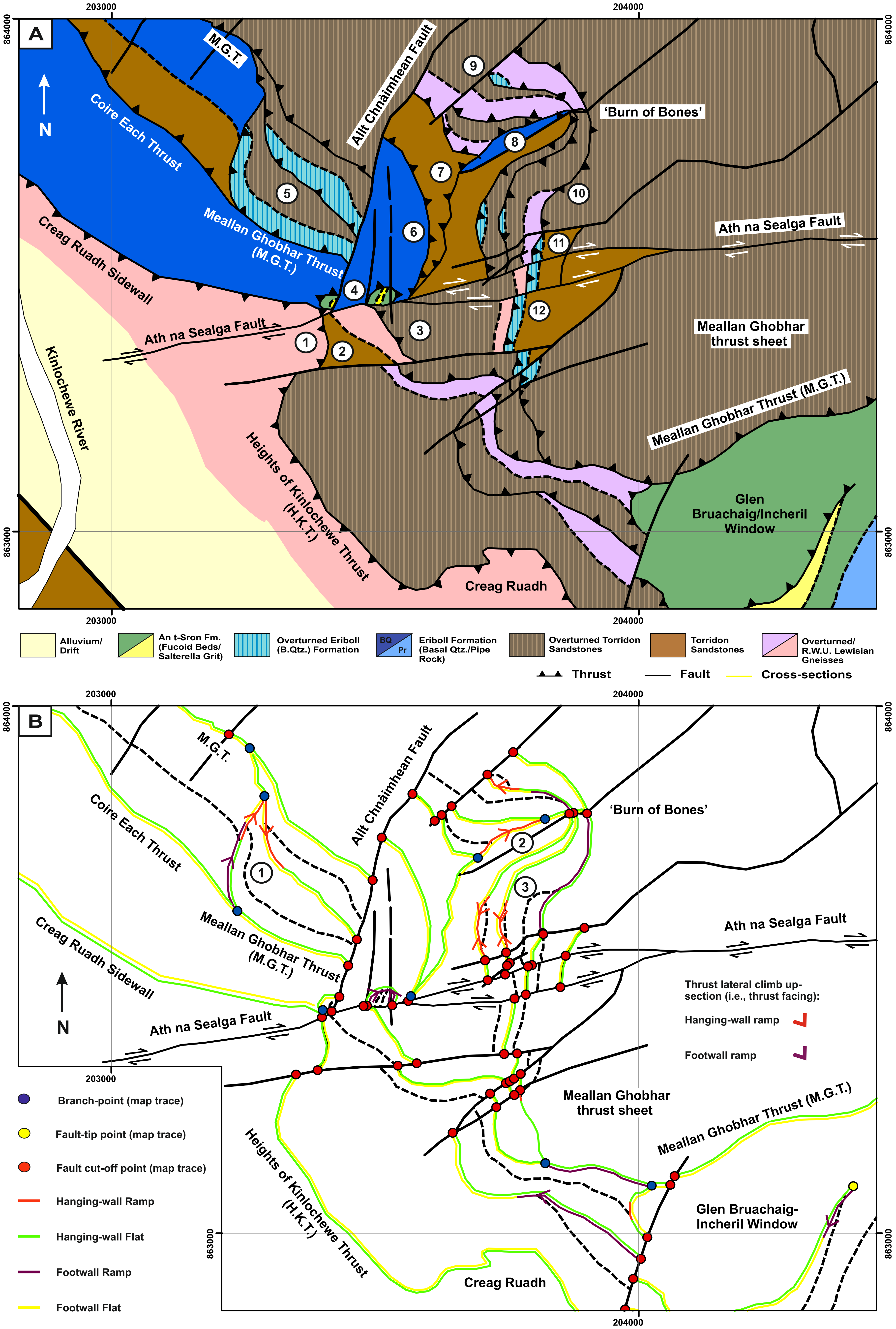


Figure 5.7: (A) Geological map of the 'Burn of Bones' domain within the Heights of Kinlochewe sector highlighting interactions of the Coire Each, Meallan Ghobhar and Heights of Kinlochewe thrust sheets together with the Ath na Sealga dextral fault system. Observations highlighted within the text are numbered. **(B)** Fault network analysis of the 'Burn of Bones' domain within the Heights of Kinlochewe sector. Few thrust ramps are observed whilst numerous fault cut-off points are identified indicating a domain dominated by brittle processes truncating and displacing the respective thrust sheets. Observations highlighted within the text are numbered.

Figure 5.8a: 'Burn of Bones domain (facing NE), comprising an 800 m-long valley within which the Allt Chnàimhean river cuts. Valley allows the three-dimensional continuity of the thrust system hinterland to foreland (i.e., SE to NW) within individual thrust sheets, such as the Coire Each, Meallan Ghobhar and Heights of Kinlochewe, along the northern wall of the Loch Maree Transverse Zone to be viewed and interpreted. Scale relevant to far hillside, not foreground.

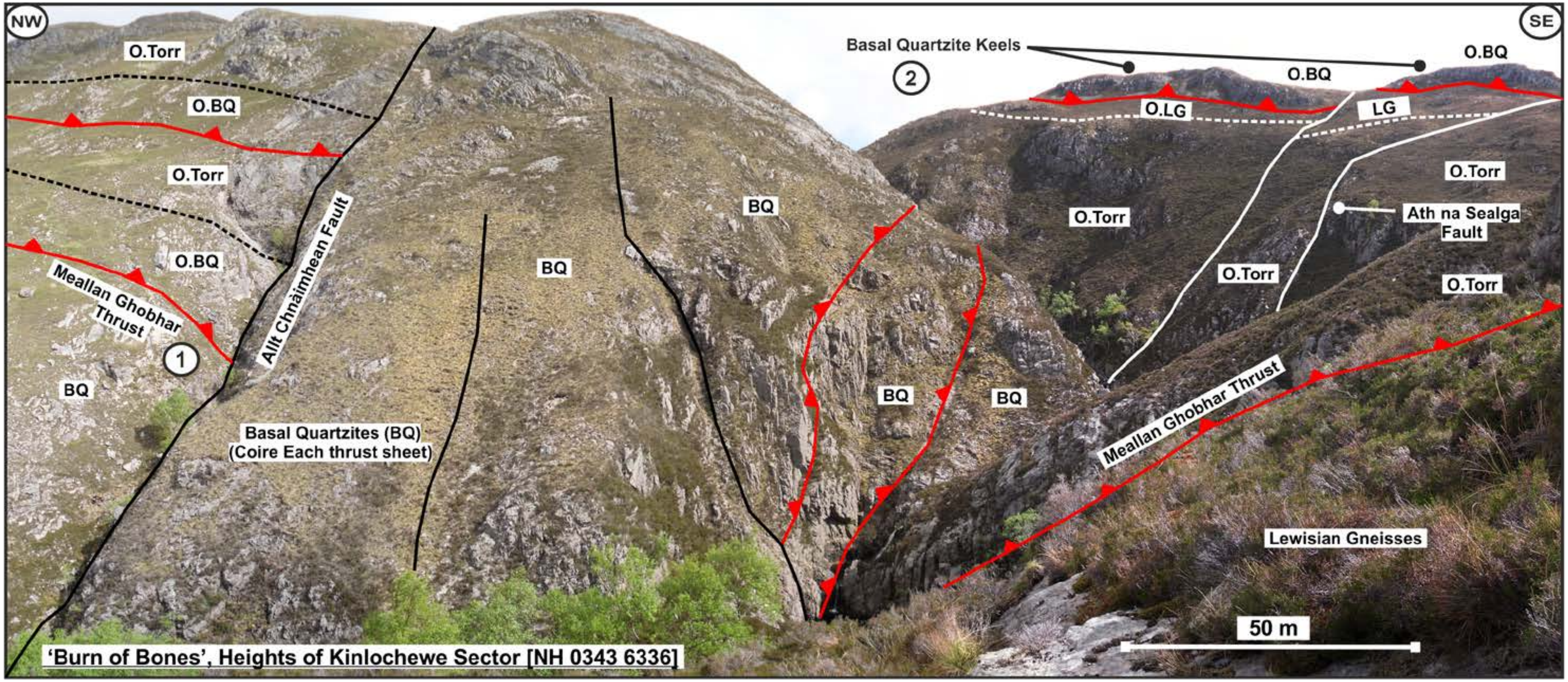


Figure 5.8b: Structural overlay of the 'Burn of Bones' domain highlighting interactions of the Coire Each (right-way-up Eriboll Formation Basal Quartzites [BQ] and Torridonian sandstones [Torr]), Meallan Ghobhar (overturned Torridonian sandstones [O.Torr], Lewisian gneisses [O.LG], and Eriboll Formation Basal Quartzites [O.BQ]) and Heights of Kinlochewe thrust sheets (right-way-up Lewisian gneisses [LG]), together with the Ath na Sealga dextral fault system. Observations highlighted in text numbered. Scale relevant to far hillside, not foreground.

dextral fault system, which displaces higher thrust sheets further down the Heights of Kinlochewe cliff line [NH 0340 6328] (Figure 5.7a; 5.8b). 'Burn of Bones' domain allows the three-dimensional continuity of the thrust system (hinterland to foreland) within individual thrust sheets along the northern wall of the Loch Maree Transverse Zone to be viewed and interpreted.

Along the lower slopes of the 'Burn of Bones' domain, Lewisian gneisses are observed lying over a right-way-up sequence of Eriboll Formation (Basal Quartzite) lithologies along a south-west dipping thrust [NH 0336 6343] (Figure 5.7a [1]). Gneisses within this lower section of the 'Burn of Bones' domain comprise the continuation of the Scourie dyke containing Lewisian units, observed within the Glen Bruachaig-Incheril Window domain (i.e., Creag Ruadh Sidewall). Hanging-wall anticlines and Scourie dykes within the Lewisian gneisses are identified along this sidewall within the north-western side of the Allt Chnàimhean valley (Figure 5.9a-c). However, unlike their Glen Bruachaig-Incheril Window counterparts at Creag Ruadh [NH 0366 6266] which are orientated horizontal to the cliff line, Scourie dykes within the 'Burn of Bones' / Allt Chnàimhean valley show little deformation and retain their sub-vertical profile cutting through the Lewisian gneisses similar to those within the foreland (northwest-southeast) [NH 0322 6340] (Figure 5.9b; 5.9c). Observations indicate along-strike deformation variations within the Creag Ruadh Sidewall.

Within the lower reaches of the 'Burn of Bones' south-eastern wall, the along-strike continuation of the thrust plane placing Lewisian gneisses over Eriboll Formation (Basal Quartzites) is identified (Figure 5.9d). At the base of this Lewisian gneiss-bearing thrust sheet (i.e., Heights of Kinlochewe), evidence of cataclastic and mylonitic units are observed along the thrust plane (Figure 5.9e) [NH 0341 6343]. Lewisian gneisses

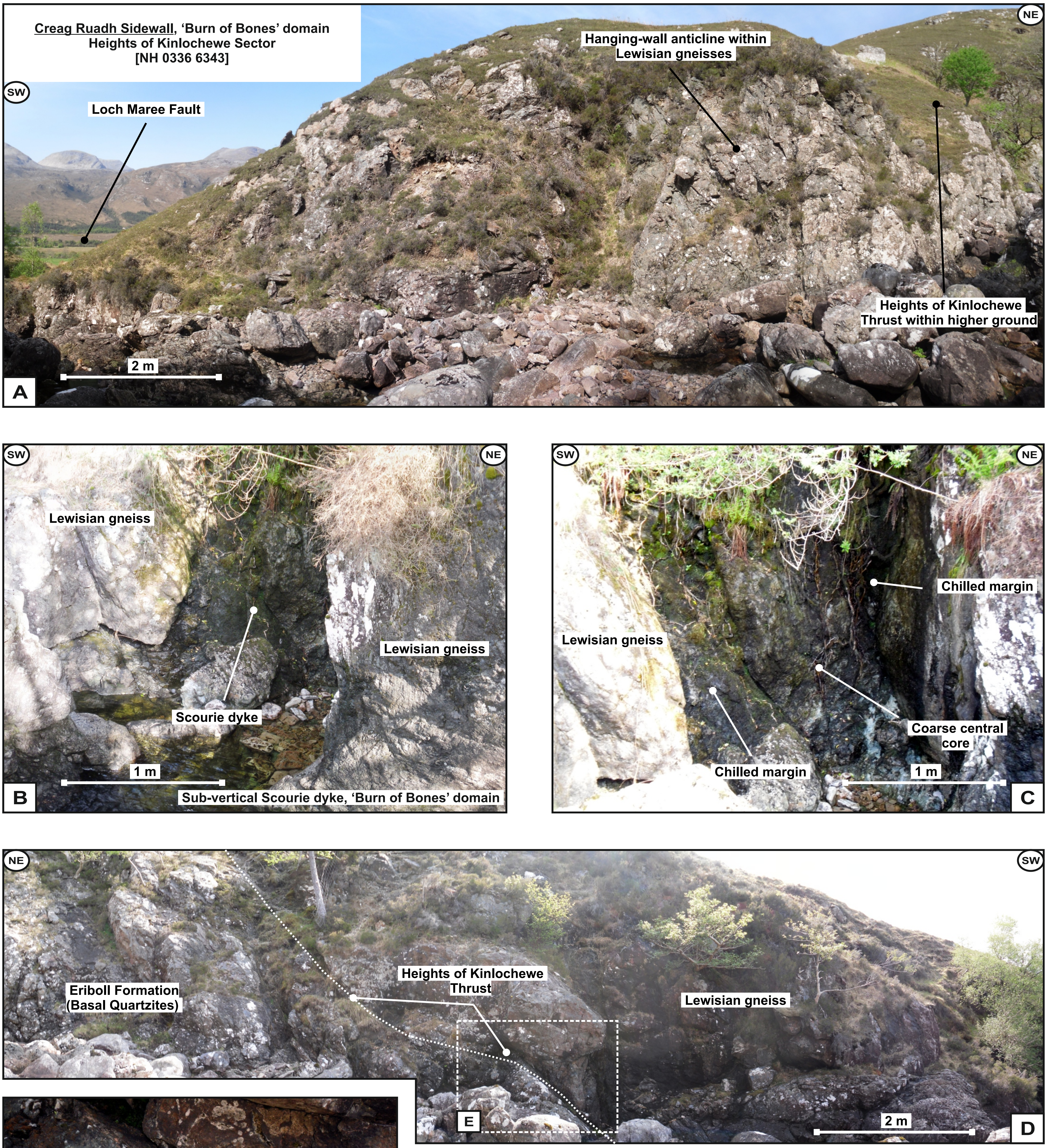


Figure 5.9: (A) Lewisian gneisses are observed lying over a right-way-up sequence of Eriboll Formation (Basal Quartzite) lithologies along a south-west dipping thrust (i.e., Creag Ruadh Sidewall) [NH 0336 6343]. Hanging-wall anticlines define the contact of the Creag Ruadh Sidewall. **(B)** Scourie dykes within the 'Burn of Bones' domain retain their sub-vertical profile, similar to those within the foreland orientated northwest-southeast. Chilled margins are identified on both sides of the dyke contact separated by a coarse grained core **(C)**.

On the southeastern side of the Allt Chnàimhean valley the along-strike continuation of the Heights of Kinlochewe thrust plane placing Lewisian gneisses over Eriboll Formation (Basal Quartzites) is identified **(D)**. At the base of this Lewisian gneiss-bearing thrust sheet (i.e., Heights of Kinlochewe), evidence of cataclastic and mylonitic units are observed along the thrust plane **(E)**.

continue along-strike south-eastward for forty metres until the Ath na Sealga dextral fault system displaces the Heights of Kinlochewe Thrust Sheet by forty two metres to the southwest [NH 0339 6340] (Figure 5.7a [2]). On the southern side of the Ath na Sealga Fault, the Heights of Kinlochewe Thrust places Lewisian gneisses over undeformed Torridonian sandstones of the Coire Each Thrust Sheet, indicating that within this lower section, the Meallan Ghobhar Thrust Sheet is cut out against the structurally higher Heights of Kinlochewe Thrust Sheet (Figure 5.7a [2]). Supportive evidence is identified one hundred ten metres northwest [NH 0352 6338], where the Meallan Ghobhar Thrust Sheet is observed placing overturned Torridonian sandstones over undeformed Lewisian gneisses (Figure 5.7a [3]).

Within the original mapping of Peach *et al.,* (1907), several windows comprising An t-Sron Formation lithologies are identified within the lower courses of the Allt Chnàimhean river. These windows are verified within this research, identifying a series of ‘pods’ along the base of the Allt Chnàimhean over a thirty five metre river section; comprising the underlying Coire Each footwall sequence (Figure 5.7a [4]; 5.10a). An t-Sron Formation (Fucoid Bed and Salterella Grit) lithologies are bounded on their eastern side by a large north-northeast-south-southwest orientated fault (i.e., Allt Chnàimhean Fault) which entrains An t-Sron Formation (Fucoid Bed) material [NH 0342 6344] (Figure 5.7a [4]; 5.10a).

Forelandward of the Allt Chnàimhean Fault, imbricated overturned Torridonian sandstone and Eriboll Formation Basal Quartzite units of the Meallan Ghobhar Thrust Sheet are displaced one hundred metres down the Heights of Kinlochewe cliff line against this fault, indicating a down-cutting of the Meallan Ghobhar Thrust within its footwall into the underlying Coire Each Thrust Sheet [NH 0345 6351] (Figure 5.7a [5]; 5.8b [1]).

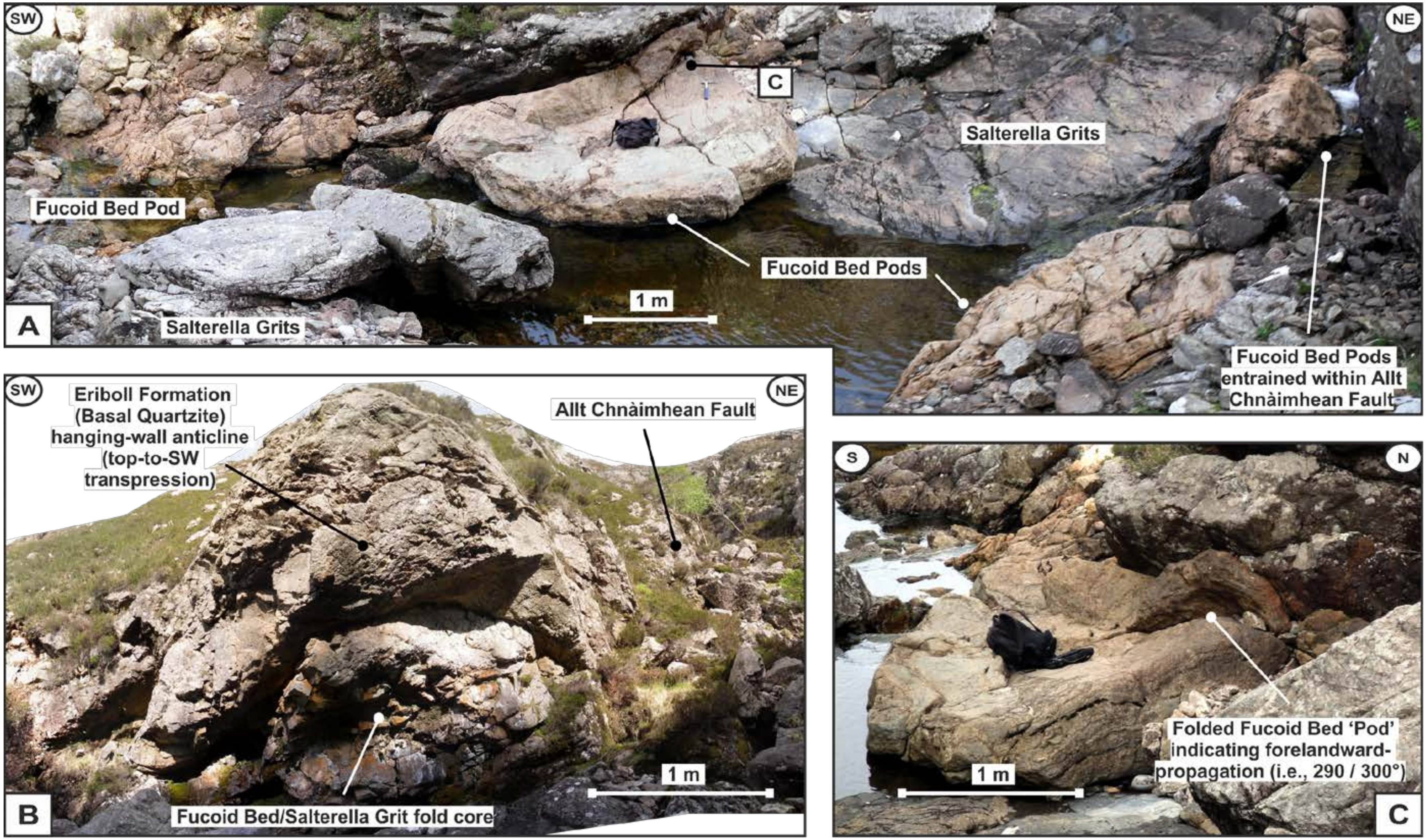


Figure 5.10: (A) Geological windows into the footwall of the Coire Each thrust sheet comprising An t-Sron Formation (Fucoid Bed and Salterella Grit) 'pods'. **(B)** Large hanging-wall anticlines observed placing Eriboll Formation Basal Quartzites over An t-Sron Formation lithologies indicating transpressional deformation towards the Loch Maree Fault (i.e., 250°). Units are bounded on their eastern side by a large north-northeast-south-southwest orientated fault (Allt Chnàimhean Fault) entraining An t-Sron Formation (Fucoid Bed) material. **(C)** An t-Sron Formation (Fucoid Beds) are folded within the regional transport direction (i.e., 290 / 300°) indicating both transpressional and regional transport directions.

Observations are supported by hanging-wall and footwall ramps identified within fault network analyses which climb the Meallan Ghobhar cliff line forelandward of the Allt Chnàimhean Fault (Figure 5.7b [1]).

Units overlying the An t-Sron Formation (Fucoid Bed and Salterella Grit) 'pods' identify hanging-wall anticlines placing right-way-up Eriboll Formation Basal Quartzites over the window sequences (Figure 5.10b). Hanging-wall anticlines are aligned northwest-southeast, sub-parallel to the regional (290 / 300°) transport direction, indicating a top-to-southwest thrust geometry, whilst the An t-Sron Formation 'pods' also indicate folding as a result of forelandward thrust translation along the Coire Each Thrust within the regional west-northwest to northwest (290 / 300°) transport direction (Figure 5.10c). Units indicate that not only is the Coire Each Thrust foreland-propagating within the lower reaches of the 'Burn of Bones' domain (top-to-northwest), but lateral transpression is also occurring against the Loch Maree Fault (top-to-southwest) as the thrust system cuts down the hillside from the top of the Heights of Kinlochewe sector.

Within the medial sections of the 'Burn of Bones' domain, a second fifty metre wide window into the Coire Each footwall is observed [NH 0350 6344] (Figure 5.7a [4]; 5.11a). Large quantities of up to one metre thick An t-Sron Formation (Fucoid Bed) units litter the floor of the window (Figure 5.11a [1]; 5.11b), whilst the Coire Each Thrust carrying right-way-up Eriboll Formation Basal Quartzites is also identified (Figure 5.11a [2]; 5.11c). An t-Sron Formation units within the second window are also bounded and truncated on their southern edge by the Ath na Sealga dextral fault system (Figure 5.7a [4]).

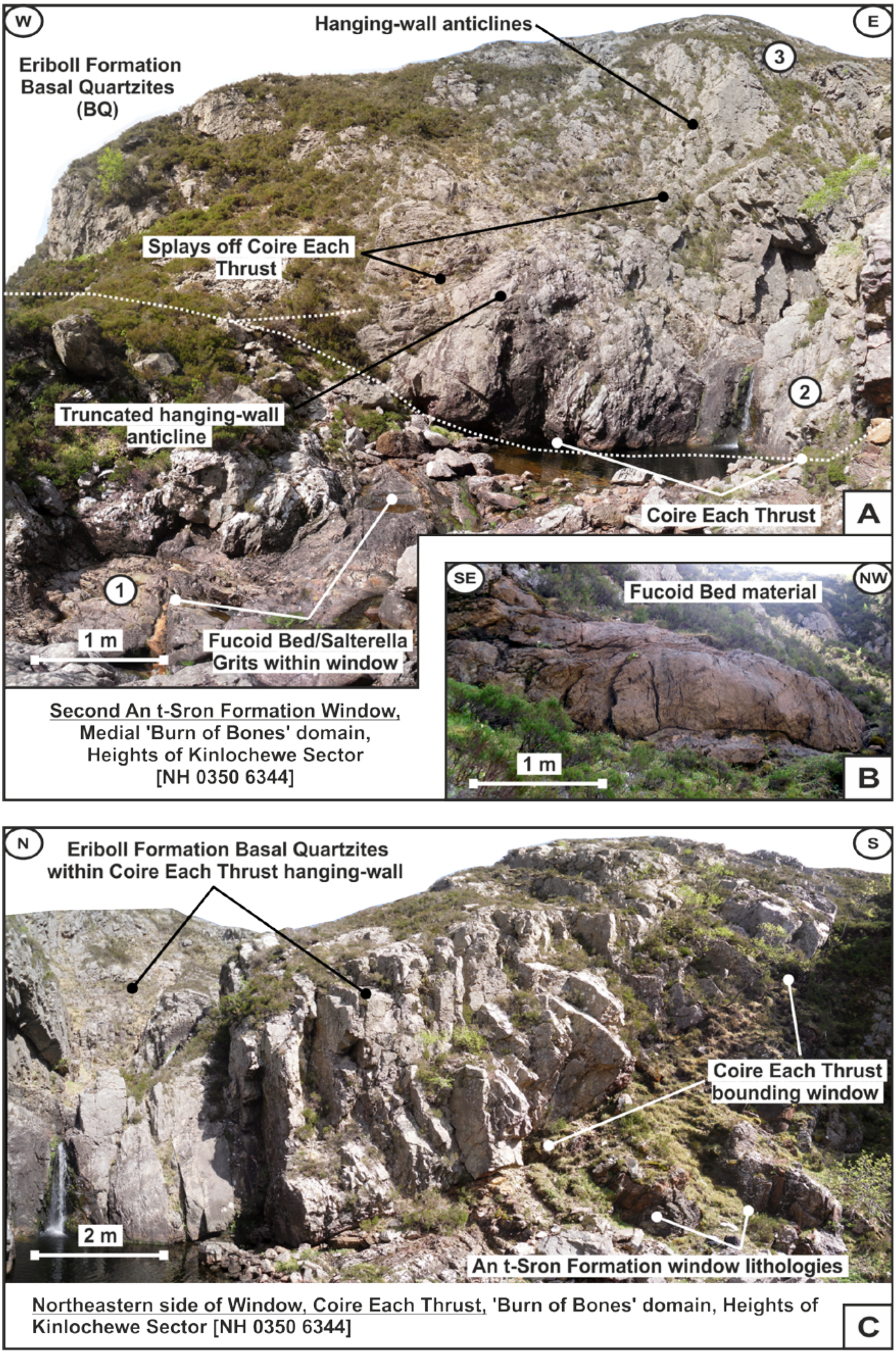


Figure 5.11: **(A)** Within the medial sections of the 'Burn of Bones' domain, a second 50 m wide window into the Coire Each footwall is observed. Large hanging-wall anticlines are identified indicating splays off the underlying Coire Each. Higher splays truncate lower splays within these sequences. **(B)** Large quantities of up to 1 m thick An t-Sron Formation (Fucoid Bed) units litter the floor of the window, whilst the Coire Each Thrust carrying right-way-up Eriboll Formation Basal Quartzite is also identified bounding the window **(C)**.

Topographically above the window section, splays off the Coire Each Thrust can be seen climbing the hillside northwards creating large (three metre plus) hanging-wall anticlines which appear to dive south-westwards into the base of the 'Burn of Bones' / Allt Chnàimhean valley [NH 0351 6351] (Figure 5.7a [6]; 5.11a [3]; 5.12). Splays containing hanging-wall anticlines truncate underlying thrust splays indicating out-of-sequence thrusting down-cutting into footwall sequences. Anticlines indicate that within this medial region of the 'Burn of Bones' domain, axial traces of the down-warping thrust sheets above the Coire Each (i.e., Meallan Ghobhar and Heights of Kinlochewe respectively) are orientated sub-parallel to the regional (290 / 300°) transport direction along the Heights of Kinlochewe cliff line, indicating transpressional deformation (Figure 5.13). Splays are truncated by the structurally higher Allt Chnàimhean Fault [NH 0351 6374] which acts as the dividing structure along the Heights of Kinlochewe cliff top between the 'Burn of Bones' domain and the Meallan Ghobhar domain (Figure 5.13).

Along the base of the 'Burn of Bones' / Allt Chnàimhean valley, the continuation of the Coire Each Thrust is observed at river level, carrying undeformed Torridonian sandstones within its hanging-wall, cutting stratigraphically up- and down-section over metre scales at the base of the Allt Chnàimhean waterfall [NH 0364 6353] (Figure 5.7a [7]; 5.14a; 5.14b). Coire Each Thrust is further identified within higher sections of the Allt Chnàimhean waterfall thirty metres upstream (Figure 5.14c; 5.14d).

Towards the head of the 'Burn of Bones' domain, interactions between the Coire Each and overlying imbricates of the Meallan Ghobhar Thrust Sheet are observed creating a long hanging-wall ramp profile [NH 0374 6375] (Figure 5.7a [8]; 5.7b [2]). The Meallan Ghobhar Thrust is identified placing hanging-wall overturned Torridonian sandstones over Eriboll Formation Basal Quartzites along the base of the Allt Chnàimhean river section

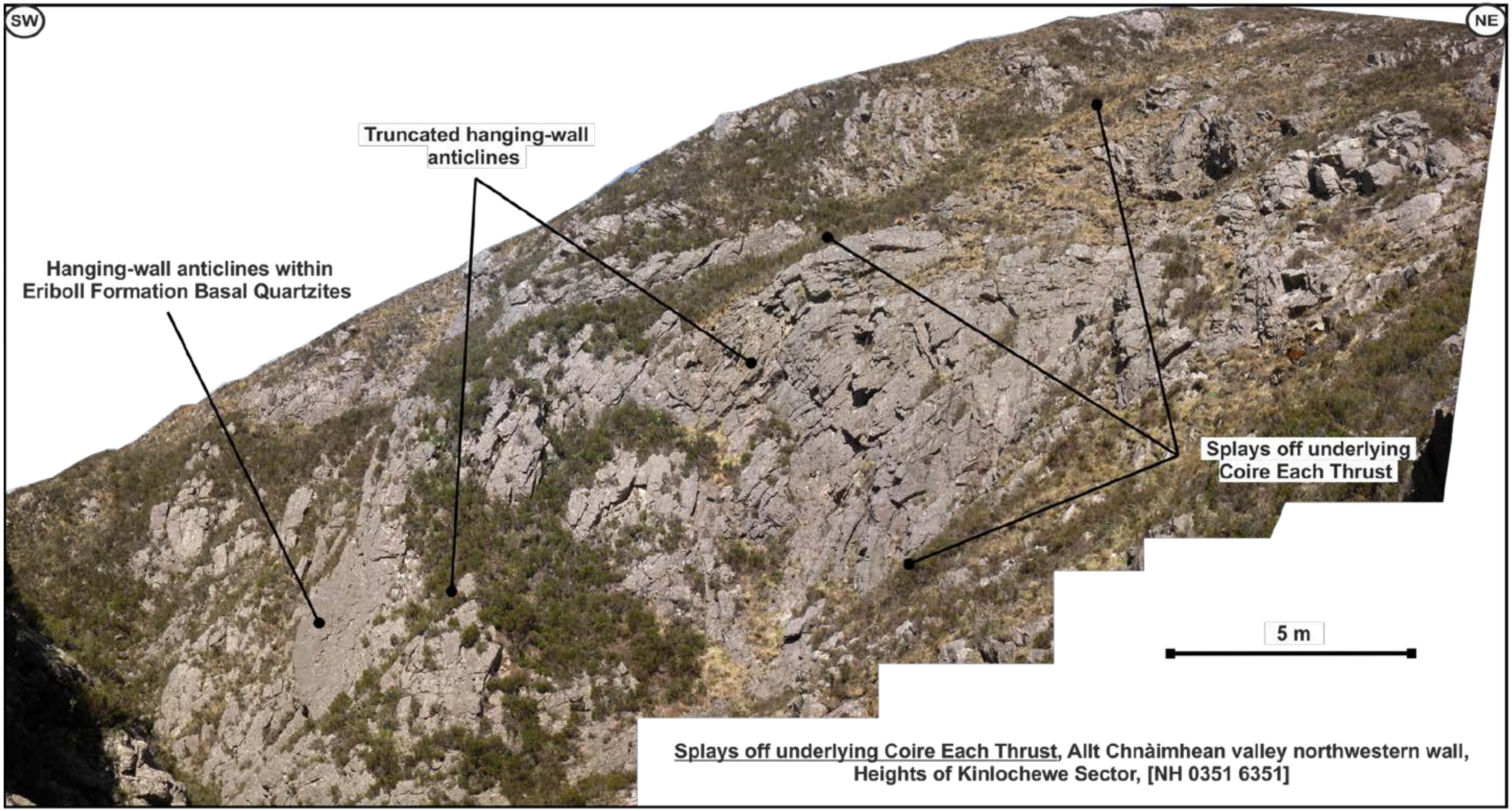


Figure 5.12: **(A)** Splays off the underlying Coire Each Thrust are identified climbing the hillside northwards creating large (3 m+) hanging-wall anticlines which appear to dive south-westwards into the base of the 'Burn of Bones'/Allt Chnàimhean valley. Higher splays truncate underlying thrusts indicating out-of-sequence thrusting within the overlying Coire Each thrust sheet. Evidence indicates a transpressional thrust transport towards the Loch Maree Fault (i.e., 250°) within a forelandward-propagating (i.e., 290 / 300°) thrust system.

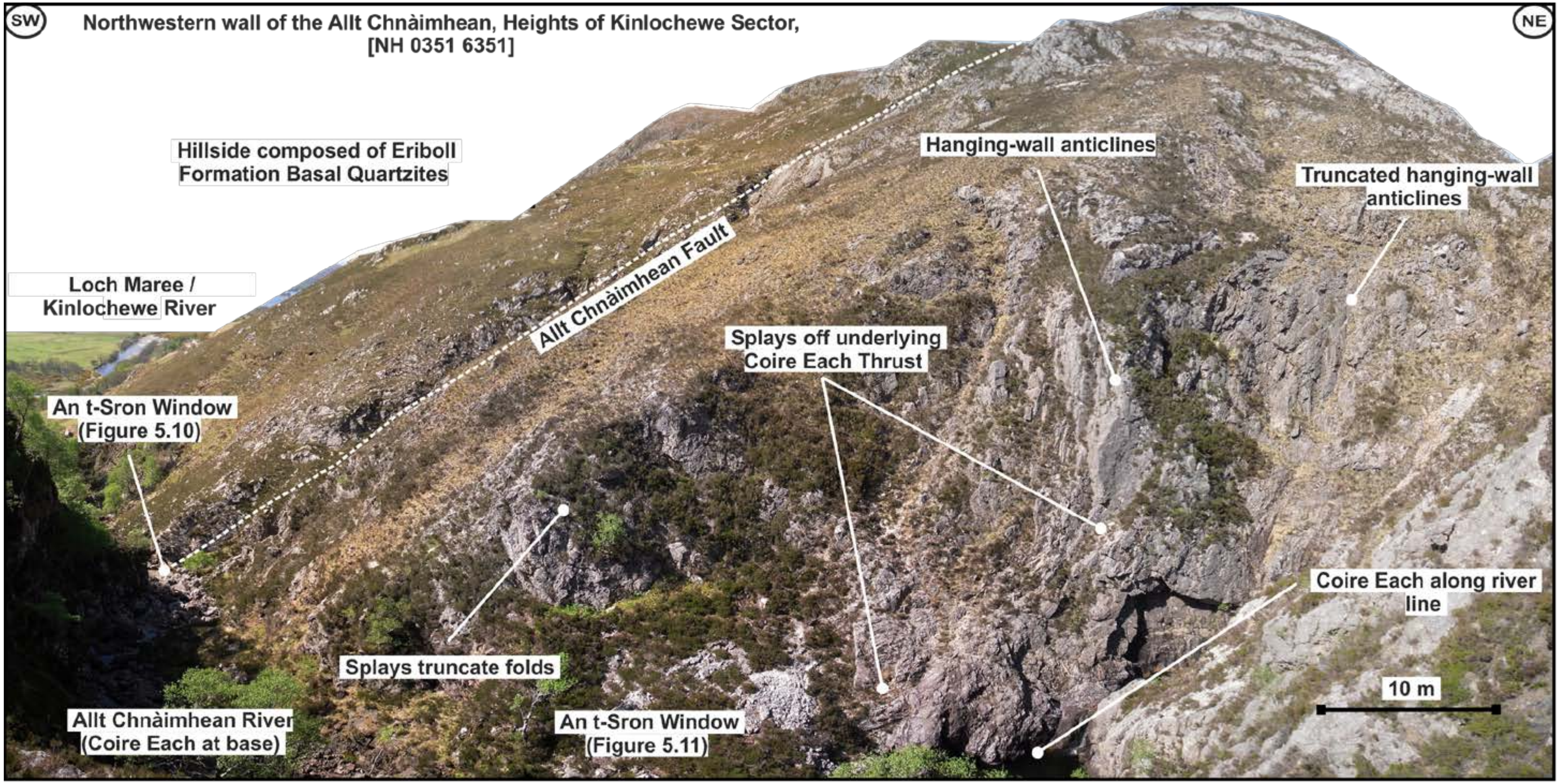


Figure 5.13: Overview of the northwestern wall of the 'Burn of Bones'/Allt Chnàimhean valley. Coire Each Thrust identified along the base of the river sequence carrying folded, right-way-up, hanging-wall sequences of Eriboll Formation Basal Quartzites. Location of major observations highlighted including, truncations of underlying thrust splays and folds indicating out-of-sequence thrusting and windows into the underlying An t-Sron Formation foreland. Evidence indicates both transpressional (i.e., 250°) and forelandward- propagating (i.e., 290 / 300°) thrust transport directions.

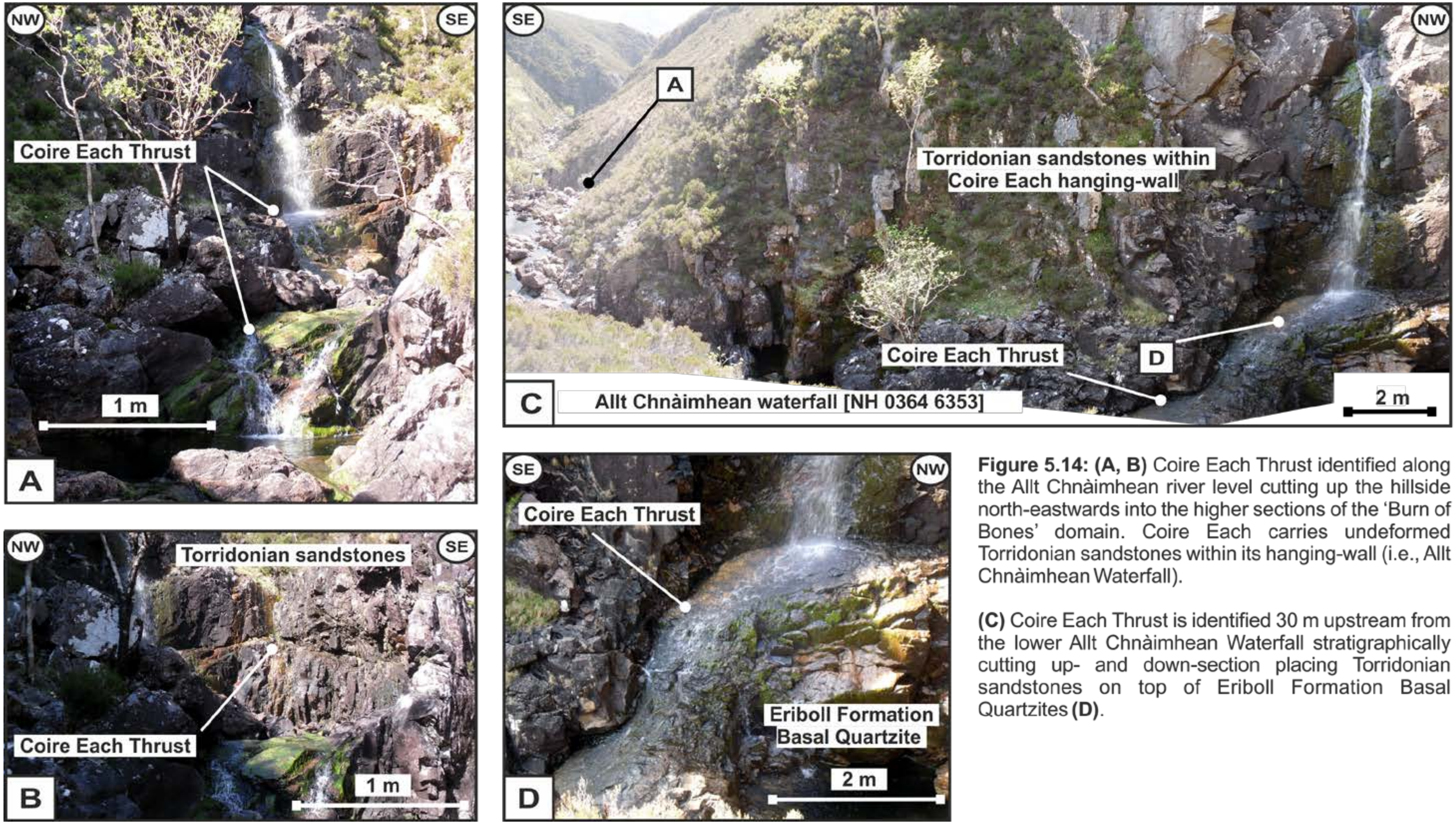


Figure 5.14: (A, B) Coire Each Thrust identified along the Allt Chnàimhean river level cutting up the hillside north-eastwards into the higher sections of the 'Burn of Bones' domain. Coire Each carries undeformed Torridonian sandstones within its hanging-wall (i.e., Allt Chnàimhean Waterfall).

(C) Coire Each Thrust is identified 30 m upstream from the lower Allt Chnàimhean Waterfall stratigraphically cutting up- and down-section placing Torridonian sandstones on top of Eriboll Formation Basal Quartzites **(D)**.

[NH 0367 6369] (Figure 5.15a). Within the footwall of the Meallan Ghobhar, large hanging-wall anticlines are identified within the Coire Each Thrust Sheet supporting a regional (290 / 300°) and transpressional (250°) thrust translation direction (Figure 5.15b). Further northeast, the Coire Each Thrust plane is observed stratigraphically cutting up- and down-section within Eriboll Formation Basal Quartzite units (Figure 5.7a [8]; 5.15c); entraining thirty centimetre strands of footwall An t-Sron Formation (Fucoid Bed) 'pods' along the Coire Each Thrust plane (Figure 5.15d).

Thirty metres northeast of this location, along the highest sections of the 'Burn of Bones' domain (i.e., Heights of Kinlochewe cliff line), the Coire Each Thrust is structurally cut-out by the overlying Meallan Ghobhar Thrust Sheet comprising complex imbricate geometries of overturned gneisses, Torridonian sandstones and Eriboll Formation (Basal Quartzite) lithologies (Figure 5.7a [9]; 5.16a-c). An overturned unconformity is also identified between overturned Lewisian gneisses and Torridonian sandstones, whilst overturned Torridonian sandstone units indicate reverse grading [NH 0366 6374] (Figure 5.16d). Imbricates containing overturned Torridonian sandstones within the hanging-wall and footwall continue along the cliff line of the Heights of Kinlochewe sector southwards along the southern wall of the 'Burn of Bones' domain (Figure 5.7a [10]).

Along the southern wall of the 'Burn of Bones' domain, several large outcrops, originally described as 'Basal Quartzite Keels' within the original map work of Peach *et al.,* (1907) are identified [NH 0377 6346] (Figure 5.17a). Structures comprise the continuation of the Meallan Ghobhar imbrications present within the 'Burn of Bones' domain along the Heights of Kinlochewe cliff line (Figure 5.7a [11]; 5.8b [2]). Within this sequence, overturned Torridonian sandstones and Eriboll Formation Basal Quartzite units containing an overturned unconformity are thrust over an overturned sequence of Lewisian gneisses

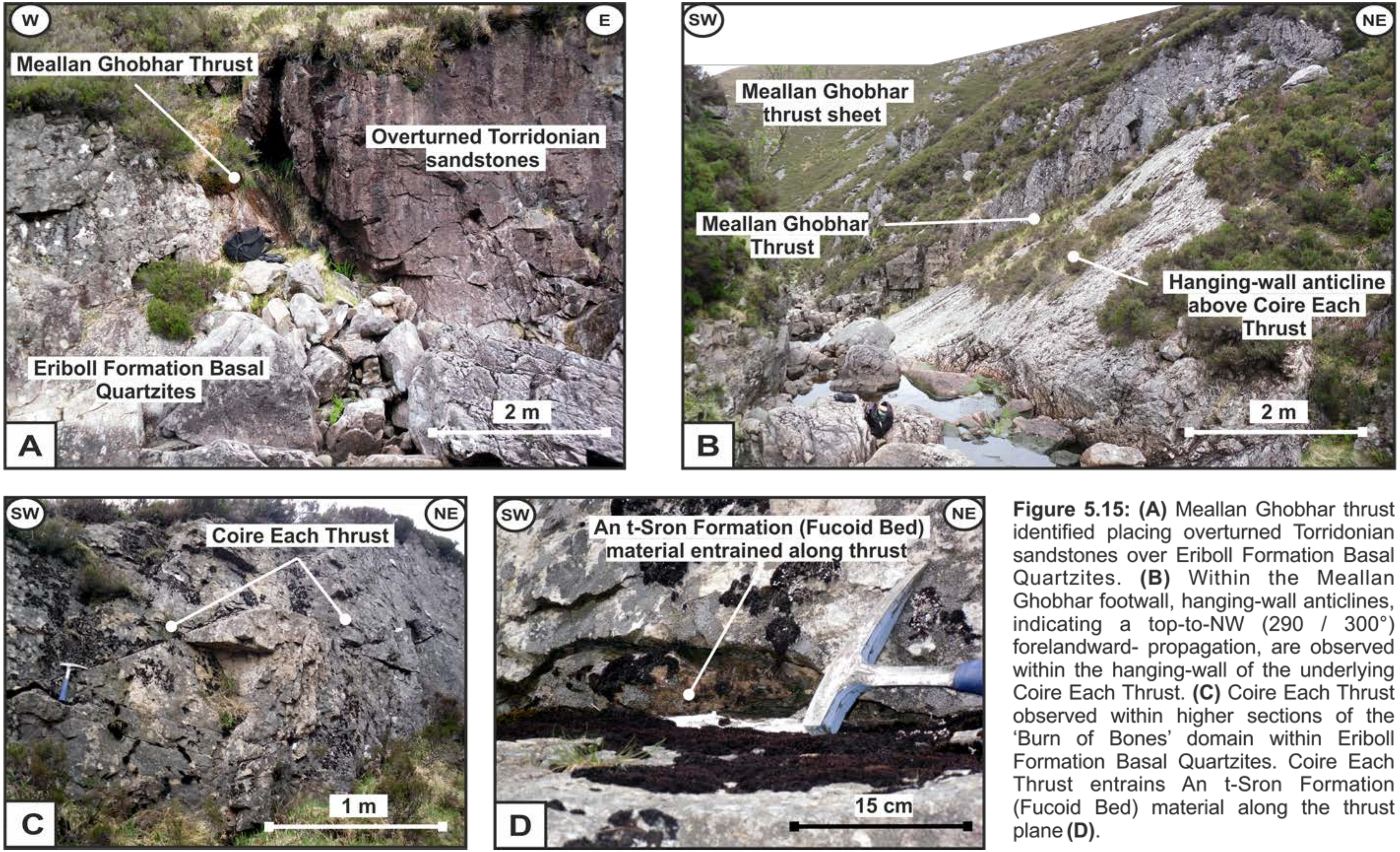


Figure 5.15: (A) Meallan Ghobhar thrust identified placing overturned Torridonian sandstones over Eriboll Formation Basal Quartzites. **(B)** Within the Meallan Ghobhar footwall, hanging-wall anticlines, indicating a top-to-NW (290 / 300°) forelandward- propagation, are observed within the hanging-wall of the underlying Coire Each Thrust. **(C)** Coire Each Thrust observed within higher sections of the 'Burn of Bones' domain within Eriboll Formation Basal Quartzites. Coire Each Thrust entrains An t-Sron Formation (Fucoid Bed) material along the thrust plane **(D)**.

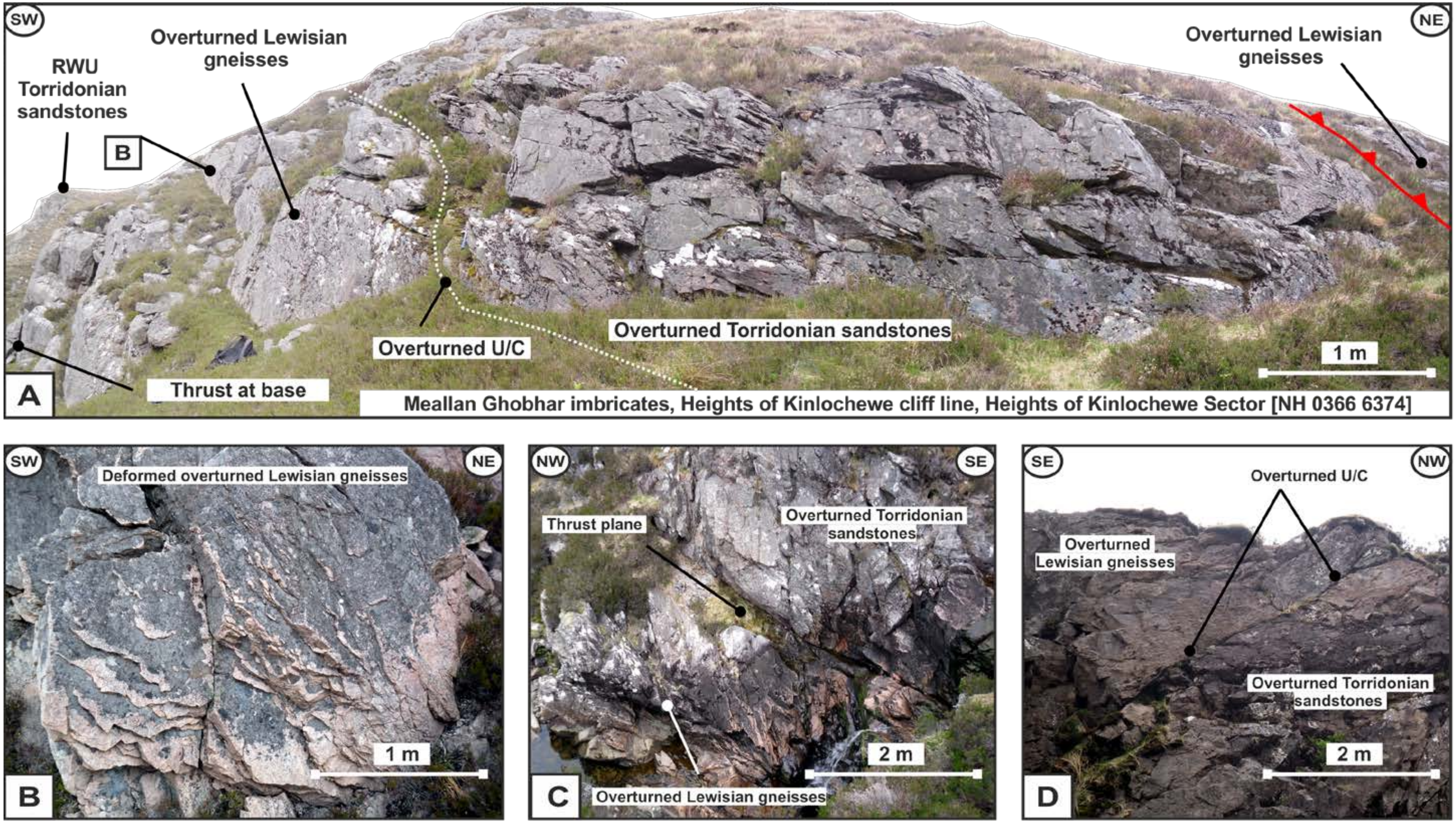


Figure 5.16: (A) Meallan Ghobhar thrust sheet identified along the Heights of Kinlochewe cliff line comprising complex imbricate geometries of overturned gneisses, Torridonian sandstones and Eriboll Formation Basal Quartzites separated by overturned unconformities (U/C). **(B)** Heavily sheared overturned Lewisian gneisses (Location highlighted in A). **(C)** Overturned Torridonian sandstones thrust over overturned Lewisian gneisses indicating thrusting along unconformity interface. **(D)** Overturned unconformity placing overturned Lewisian gneisses over overturned Torridonian sandstones.

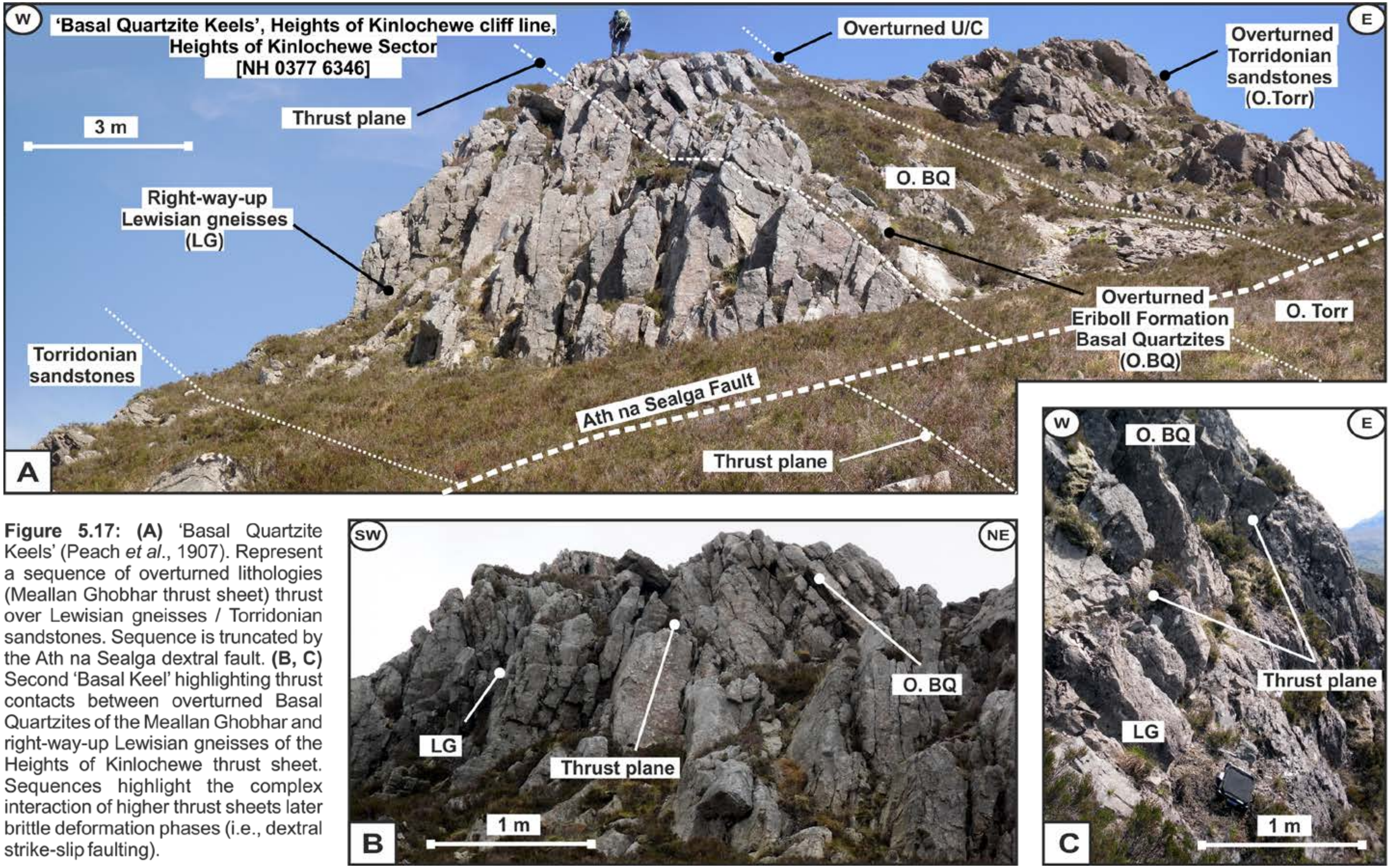


Figure 5.17: (A) 'Basal Quartzite Keels' (Peach *et al*., 1907). Represent a sequence of overturned lithologies (Meallan Ghobhar thrust sheet) thrust over Lewisian gneisses / Torridonian sandstones. Sequence is truncated by the Ath na Sealga dextral fault. **(B, C)** Second 'Basal Keel' highlighting thrust contacts between overturned Basal Quartzites of the Meallan Ghobhar and right-way-up Lewisian gneisses of the Heights of Kinlochewe thrust sheet. Sequences highlight the complex interaction of higher thrust sheets later brittle deformation phases (i.e., dextral strike-slip faulting).

and Torridonian sandstones, creating hanging-wall and footwall ramps within fault network analyses (Figure 5.7a [11]; 5.7b [3]; 5.17a-c). A second overturned unconformity between Lewisian gneisses and Torridonian sandstones is also observed ten metres further south down the Heights of Kinlochewe cliff line [NH 0376 6346] (Figure 5.17a). Thrust imbricates are truncated and displaced by the dextral Ath na Sealga Fault, indicating that brittle faulting occurs as a later development phase within the Heights of Kinlochewe sector (Figure 5.7a [12]; 5.8b [1]; 5.17a).

5.1.3. Meallan Ghobhar domain

The Meallan Ghobhar domain is dominated by the crags of Meallan Ghobhar (four hundred and sixty eight metres) [NH 0285 6460], within which complex thrust geometries are identified producing hanging-wall and footwall ramps, resulting from interactions between the Coire Each and Meallan Ghobhar thrust sheets (Figure 5.2b [4]; 5.18a [1]; 5.18b [1]; 5.19). This domain is dominated by branch-lines highlighting a bifurcating thrust network within map-view, as several thrust sheets with different rheological properties and deformation behaviours interact within this segment of the Heights of Kinlochewe sector (Figure 5.18b [1]). Underlying these thrust sheets, the lower slopes of the Meallan Ghobhar domain from Bac ‘an t-Sniomha [NH 0246 6437] to Bonaid Dhonn [NH 0220 6575] are dominated by undeformed, southeast-dipping foreland lithologies, comprising Torridonian sandstones (three hundred metres), Eriboll Formation quartzites (two hundred metres) and An t-Sron Formation units (thirty metres) (Figure 5.18a [2]; 5.19b [1]).

Along the base of the Meallan Ghobhar domain, gneisses of the Heights of Kinlochewe Thrust Sheet lie on the right way-up stratigraphy of the Coire Each Thrust Sheet [NH 0240 6393]. Gneisses are separated from the Meallan Ghobhar cliff by several vertical faults

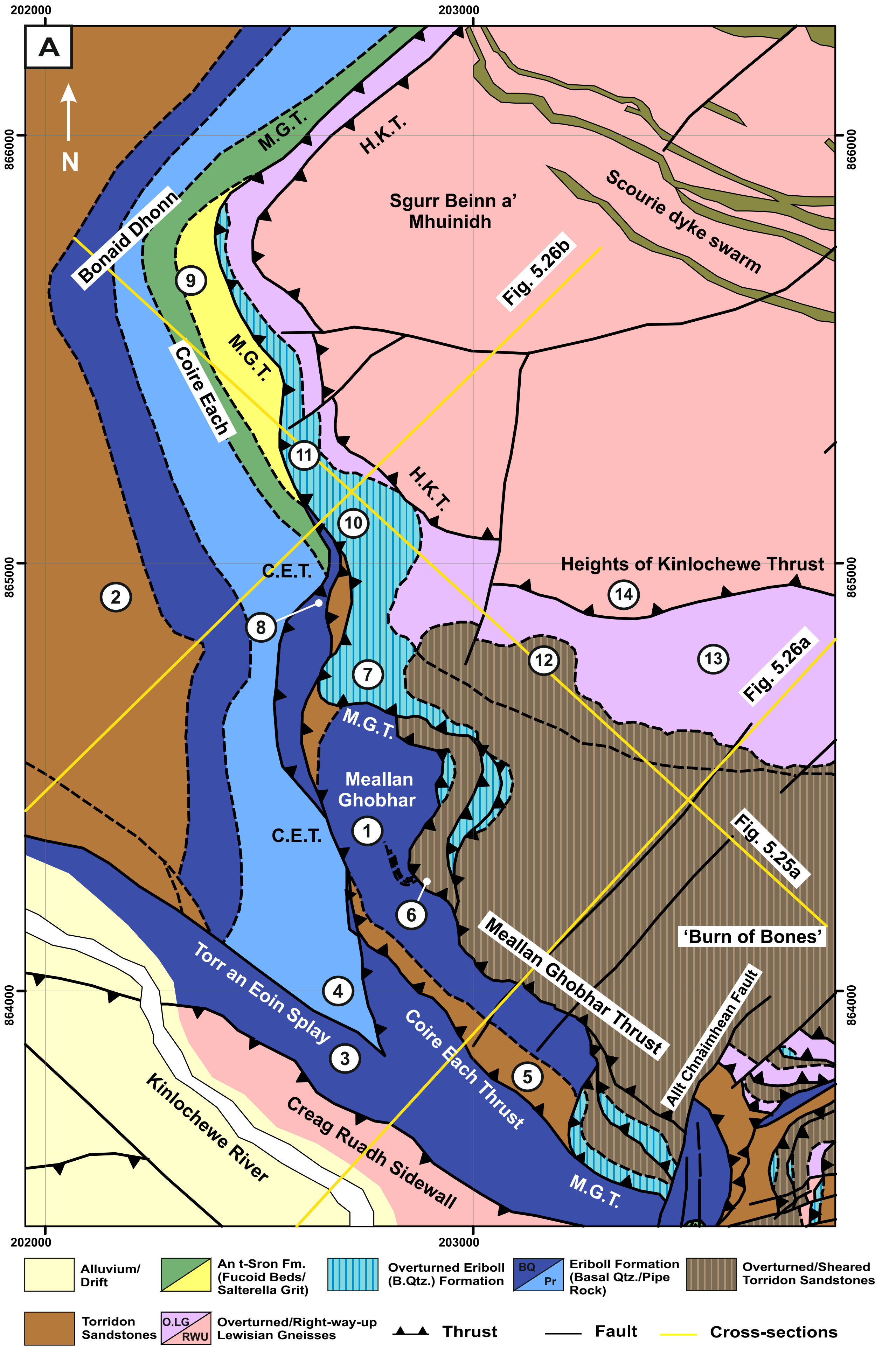


Figure 5.18a: Geological map of the Meallan Ghobhar domain, Heights of Kinlochewe sector, comprising interactions of the Coire Each, Meallan Ghobhar and Heights of Kinlochewe thrust sheets along the Meallan Ghobhar Hillside. Truncations of lower thrust sheets are identified. Observations highlighted within the text are numbered.

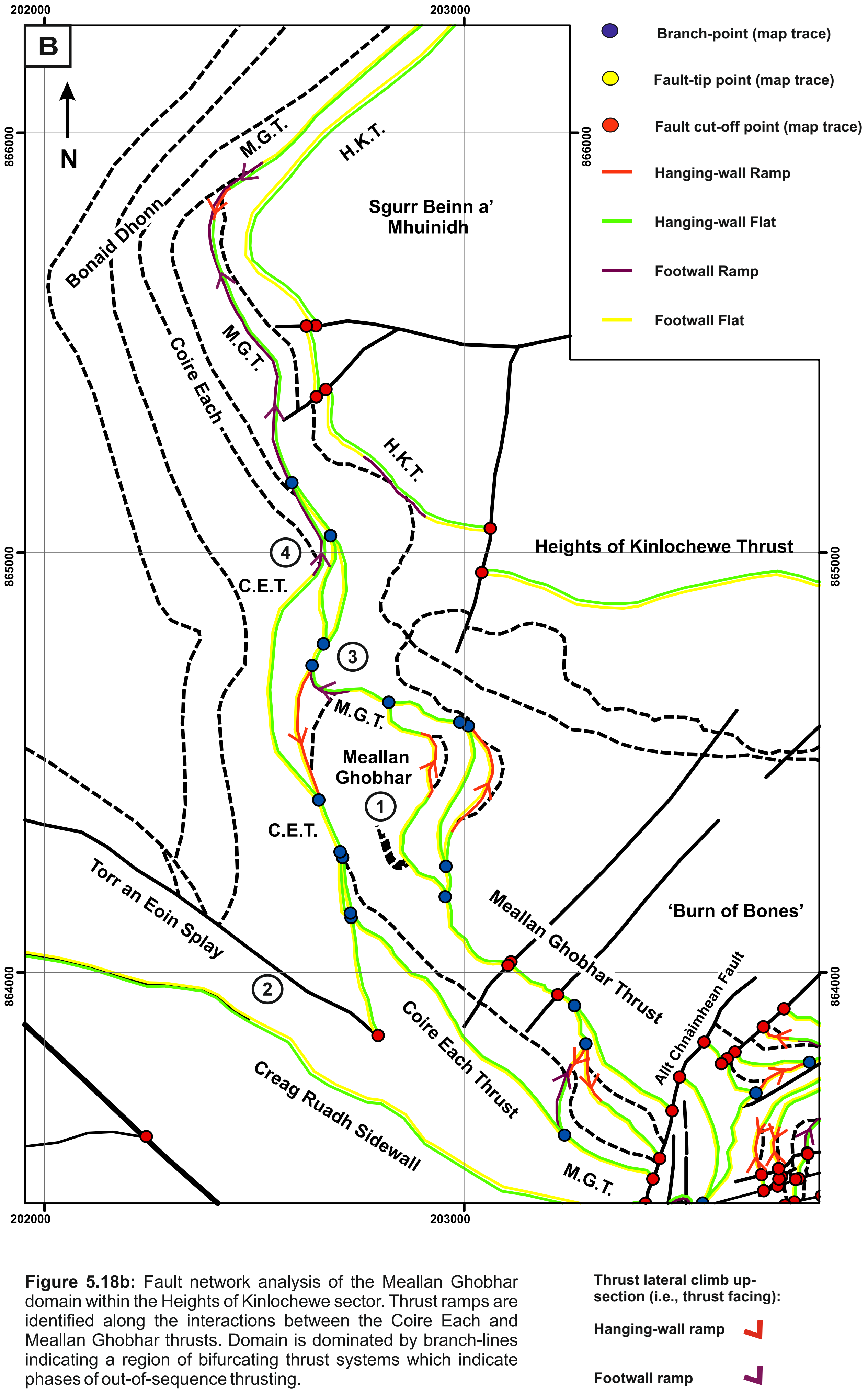


Figure 5.18b: Fault network analysis of the Meallan Ghobhar domain within the Heights of Kinlochewe sector. Thrust ramps are identified along the interactions between the Coire Each and Meallan Ghobhar thrusts. Domain is dominated by branch-lines indicating a region of bifurcating thrust systems which indicate phases of out-of-sequence thrusting.

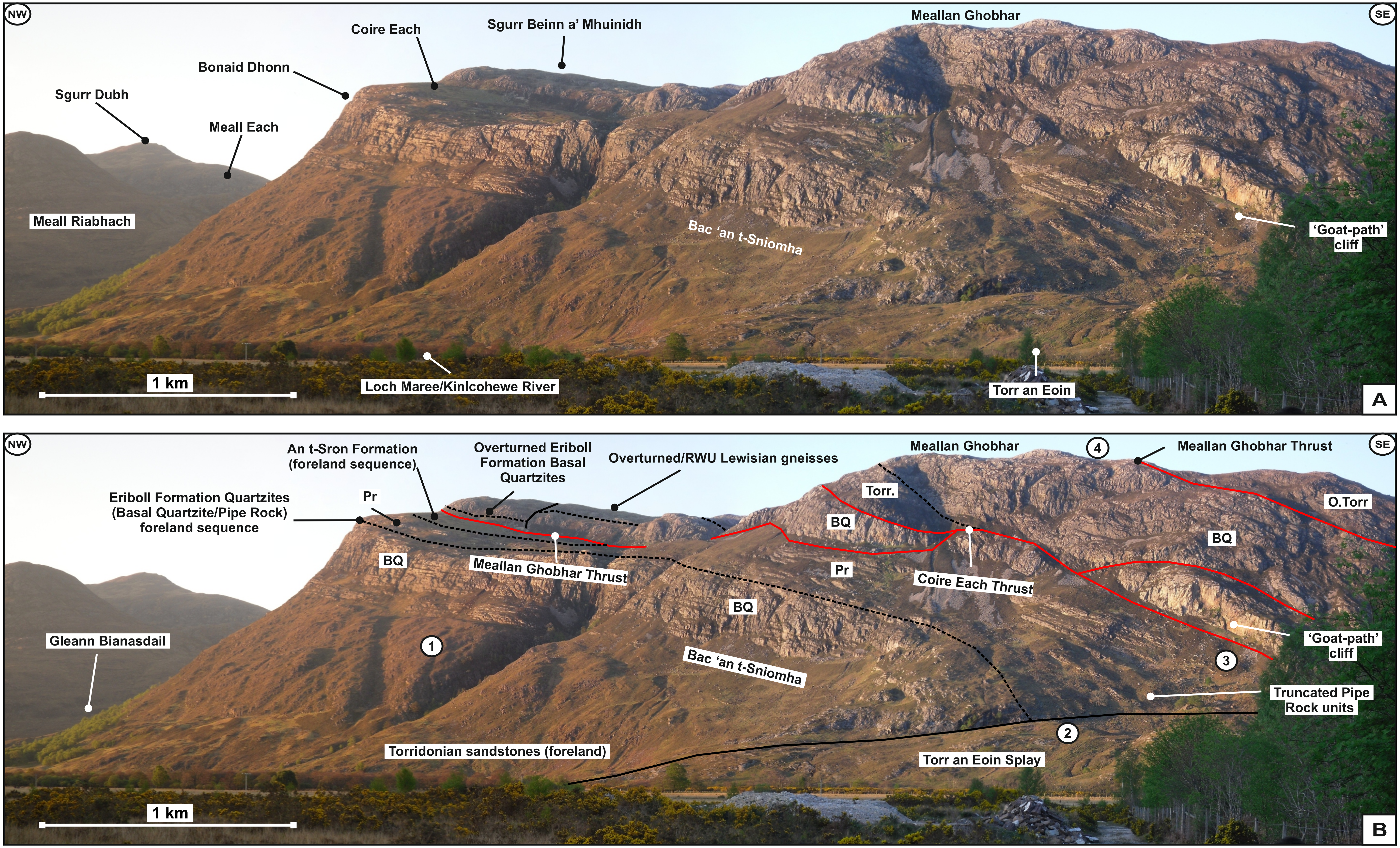


Figure 5.19: (A) Overview of the Meallan Ghobhar, Coire Each and Boniad Dhonn hillsides along the Heights of Kinlochewe cliff cline.

(B) Structural overlay highlighting interactions of the Coire Each, Meallan Ghobhar and Heights of Kinlochewe thrusts (red lines) and their respective thrust sheets along the Heights of Kinlochewe cliff line. Thrust interactions indicate out of sequence thrusting within these hillsides, with underlying thrust sheets being truncated by structurally higher thrusts (i.e., truncation of the Coire Each by Meallan Ghobhar). Interactions with the Loch Maree Fault system are also observed along Torr an Eoin. Observations highlighted within the text numbered.

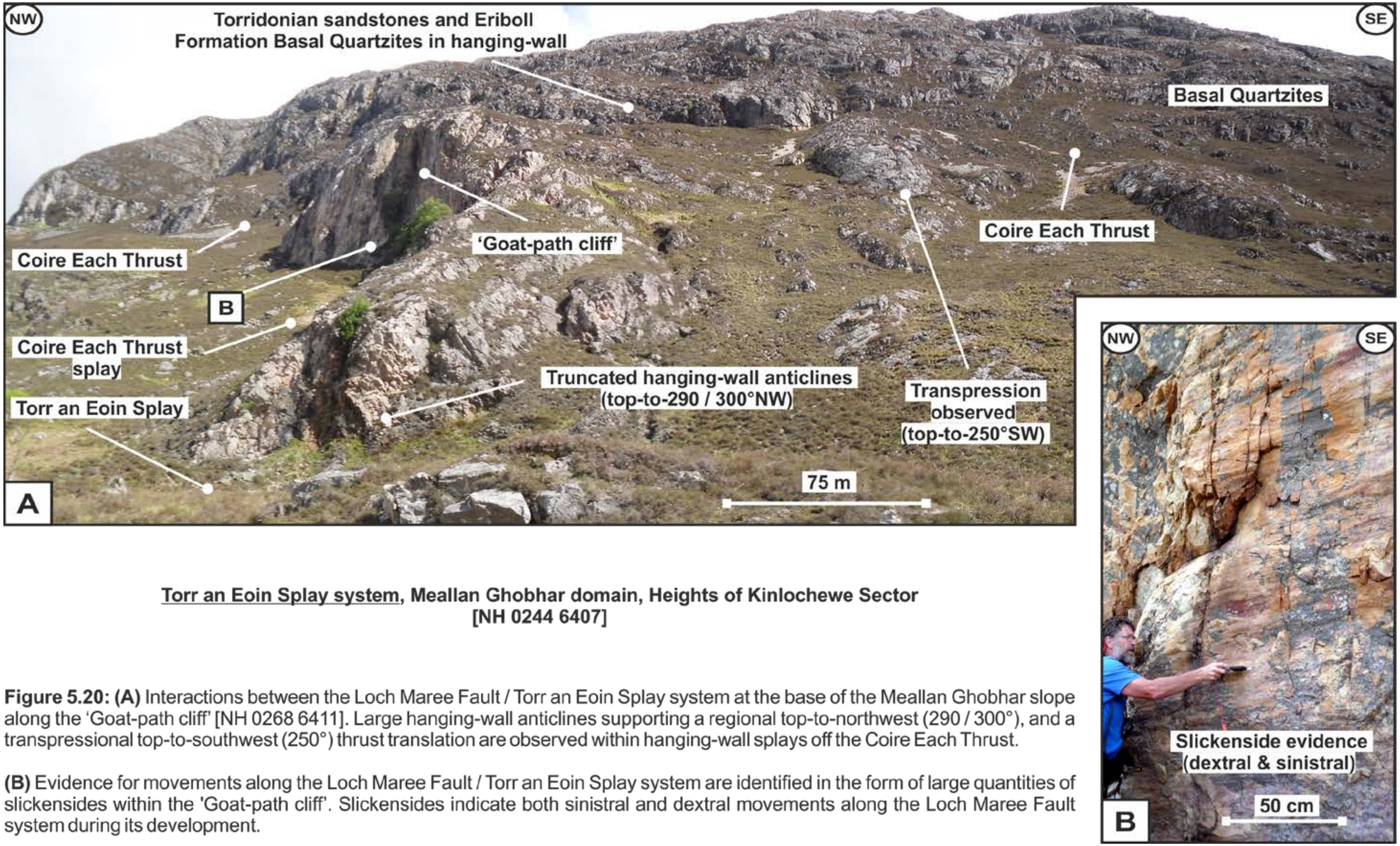
Meallan Ghobhar, Coire Each and Boniad Dhonn hillsides. Meallan Ghobhar domain,

Heights of Kinlochewe Sector [NH 0285 6460]

which form part of the Loch Maree Fault (LMF) system along its northern edge within Eriboll Formation Basal Quartzites (i.e., Torr an Eoin Splay [NH 0244 6407]; Figure 5.18a [3]; 5.18b [2]; 5.19b [2]). Northeast of this fault splay system, along the base of the Meallan Ghobhar slope, interactions of the Loch Maree Fault system are identified in the form of large quantities of slickensides within the 'Goat-path cliff' [NH 0268 6411] (Figure 5.18a [4]; 5.19b [3]; 5.20a; 5.20b). Slickensides indicate both sinistral and dextral movements along the Loch Maree Fault system during its development.

The Coire Each Thrust Sheet, comprising right-way-up Torridonian sandstones and Eriboll Formation Basal Quartzite lithologies, can be traced laterally southeast almost to the 'Burn of Bones' domain where higher thrusts of the Meallan Ghobhar truncate these units within its footwall [NH 0331 6372] (Figure 5.18a [5]; 5.18b; 5.20a). At the base of the Meallan Ghobhar cliff line, large hanging-wall anticlines supporting a regional top-to-northwest (290 / 300°), and a transpressional top-to-southwest (250°) thrust translation are observed within a hanging-wall splay off the Coire Each Thrust (Figure 5.20a). Further evidence supporting these observations is identified as the Coire Each Thrust climbs north-westwards along the Meallan Ghobhar cliff line, carrying Torridonian sandstones and Eriboll Formation Basal Quartzites within its hanging-wall. Within these hanging-wall units, large (one hundred metre) folds orientated northeast-southwest are identified within the one hundred fifty metre thick Eriboll Formation quartzites [NH 0282 6428], indicating a top-to-northwest (290 / 300°) transport direction (Figure 5.19b [4]; 5.21a). At outcrop scale, these units drastically overturn at very steep angles (Figure 5.21b; 5.21c).

Structurally overlying these Coire Each folded units, the Meallan Ghobhar Thrust is traced climbing the northwest slope to the Meallan Ghobhar summit, carrying overturned sequences of Torridonian sandstones and Eriboll Formation Basal Quartzites within its



Torr an Eoin Splay system, Meallan Ghobhar domain, Heights of Kinlochewe Sector
[NH 0244 6407]

Figure 5.20: (A) Interactions between the Loch Maree Fault / Torr an Eoin Splay system at the base of the Meallan Ghobhar slope along the 'Goat-path cliff' [NH 0268 6411]. Large hanging-wall anticlines supporting a regional top-to-northwest (290 / 300°), and a transpressional top-to-southwest (250°) thrust translation are observed within hanging-wall splays off the Coire Each Thrust.

(B) Evidence for movements along the Loch Maree Fault / Torr an Eoin Splay system are identified in the form of large quantities of slickensides within the 'Goat-path cliff'. Slickensides indicate both sinistral and dextral movements along the Loch Maree Fault system during its development.

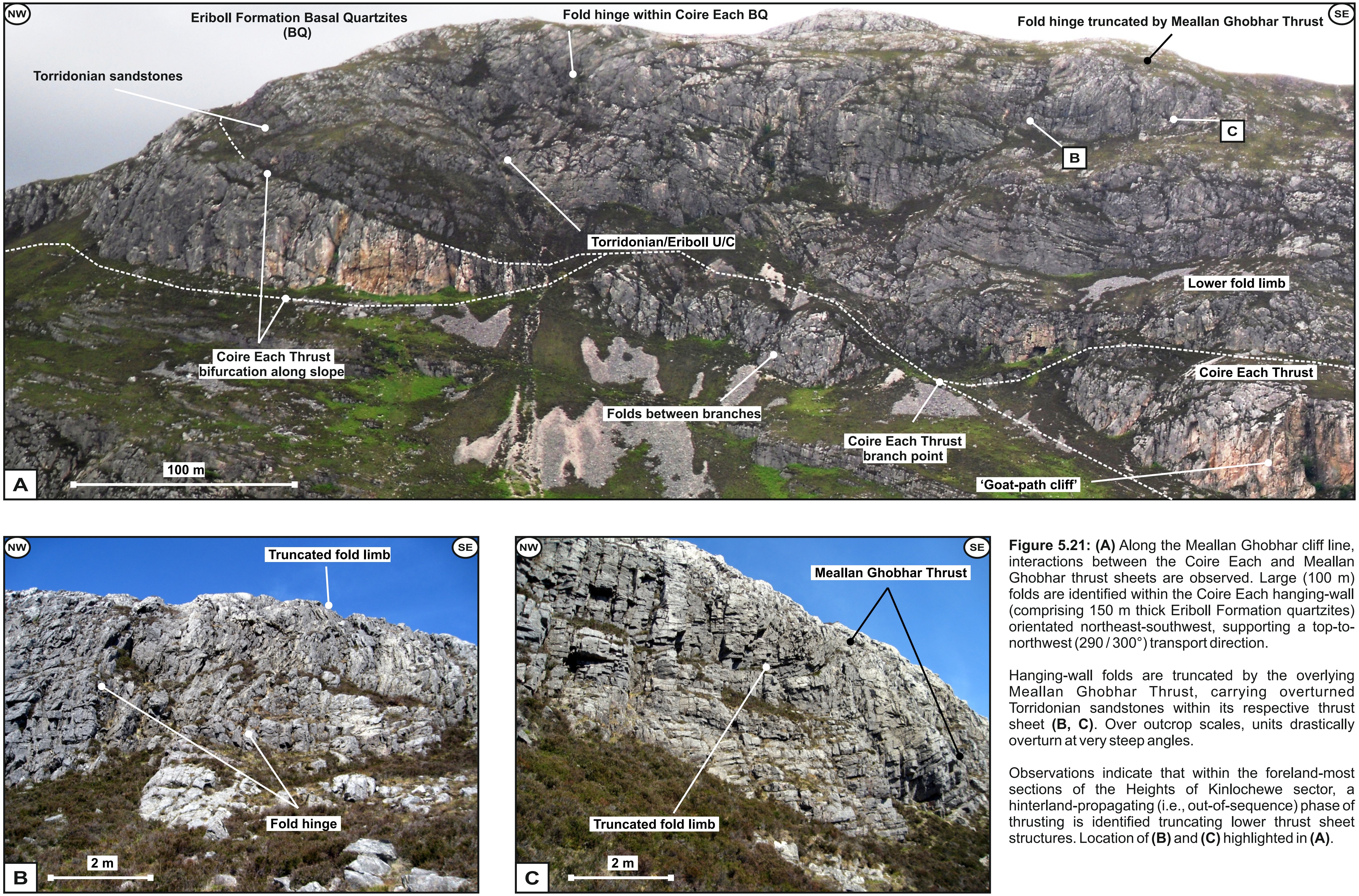


Figure 5.21: (A) Along the Meallan Ghobhar cliff line, interactions between the Coire Each and Meallan Ghobhar thrust sheets are observed. Large (100 m) folds are identified within the Coire Each hanging-wall (comprising 150 m thick Eriboll Formation quartzites) orientated northeast-southwest, supporting a top-to-northwest (290 / 300°) transport direction.

Hanging-wall folds are truncated by the overlying Meallan Ghobhar Thrust, carrying overturned Torridonian sandstones within its respective thrust sheet **(B, C)**. Over outcrop scales, units drastically overturn at very steep angles.

Observations indicate that within the foreland-most sections of the Heights of Kinlochewe sector, a hinterland-propagating (i.e., out-of-sequence) phase of thrusting is identified truncating lower thrust sheet structures. Location of **(B)** and **(C)** highlighted in **(A)**.

hanging-wall (Figure 5.18a [6]; 5.19b [4]). Fold sets within the Coire Each Thrust Sheet are truncated by the overriding Meallan Ghobhar Thrust (Figure 5.18a [6]; 5.19b [4]; 5.21). This indicates that within forelandmost sections of the Heights of Kinlochewe sector, a hinterland-propagating (i.e., out-of-sequence) phase of thrusting is identified truncating lower thrust sheet structures (Figure 5.18a [6, 7]). Along the northwest front of the Meallan Ghobhar summit (i.e., Coire Each plateau [NH 0262 6491]), transpressive deformation structures are observed within the Coire Each and Meallan Ghobhar thrust sheets indicating transport-parallel and transport-lateral compression along planes of intersection (Figure 5.18a [8]; 5.22a-c). The Meallan Ghobhar Thrust Sheet, carrying overturned 'pebbly' Basal Quartzite units, truncates these structures on their northeast flank [NH 0271 6496] (Figure 5.22c).

Within the Coire Each plateau, An t-Sron Formation lithologies (Fucoid Bed and Salterella Grits) create a two hundred eighty metre topographically-flat, southeast-dipping slope (Figure 5.18a [9]; 5.22a [1]; 5.23a). Along the northwest flank of this slope, the Meallan Ghobhar Thrust completely truncates the underlying Coire Each Thrust Sheet [NH 0259 6515] carrying fifty metres of overturned 'pebbly' Eriboll Formation Basal Quartzites within its hanging-wall over foreland An t-Sron Formation lithologies (Figure 5.18a [10]), further supporting a phase of out-of-sequence thrusting. Structurally above this, the overturned unconformity between 'pebbly' Basal Quartzites and Lewisian gneisses is viewed (Figure 5.18a [11]; 5.22a [2]; 5.23b). Out-of-sequence truncations of the Coire Each Thrust are identified within fault network analyses as a series of footwall ramps indicating a system down-cutting within its respective footwall (Figure 5.18b [3, 4]). Within the Meallan Ghobhar hanging-wall of the Meallan Ghobhar Thrust, along the eponymous hillside, units change from thick sequences of overturned Torridonian sandstones to dominant overturned 'pebbly' Eriboll Formation Basal Quartzites indicating that the Meallan Ghobhar Thrust is cutting-up stratigraphically towards the foreland (Figure 5.18a [6, 7]).

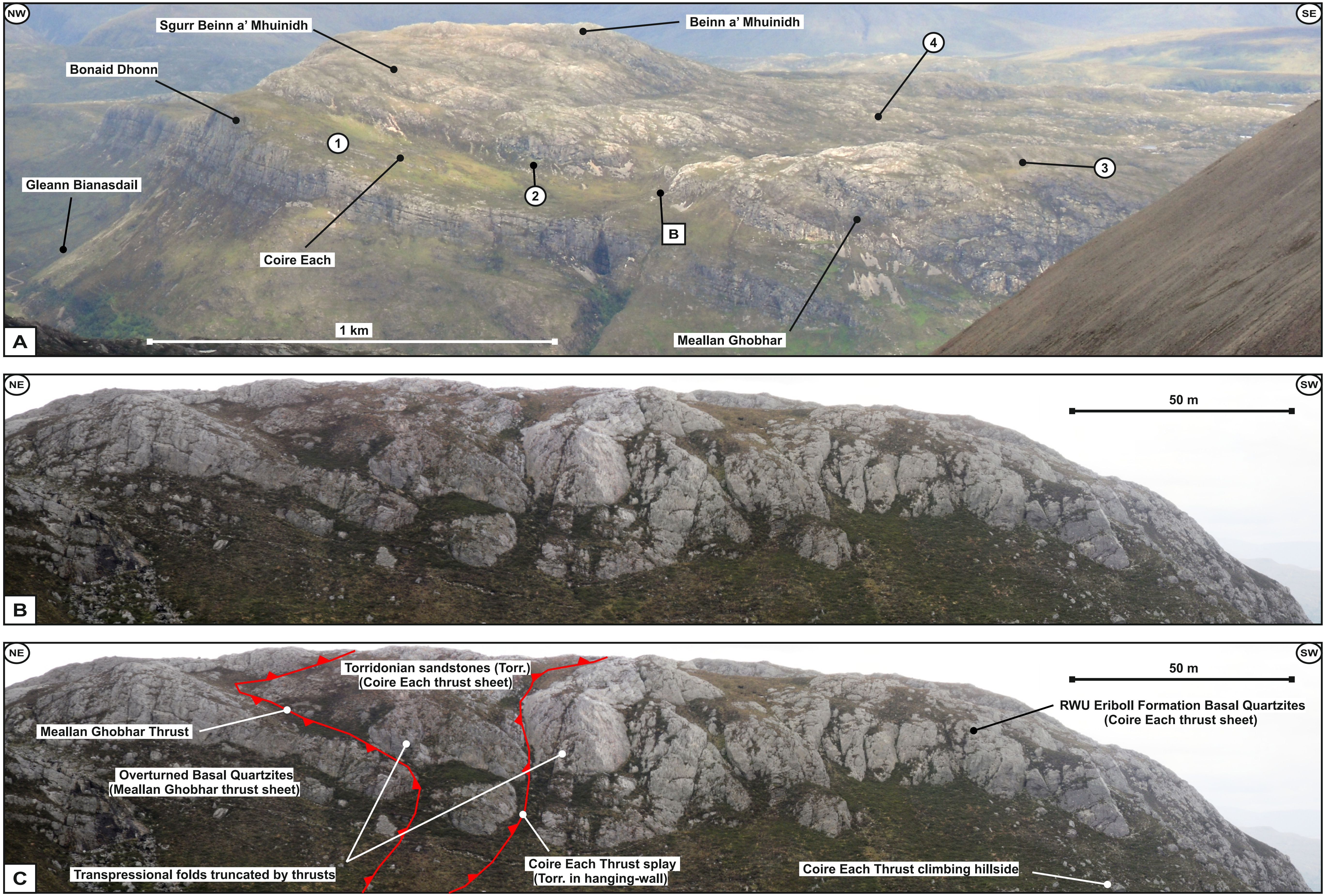
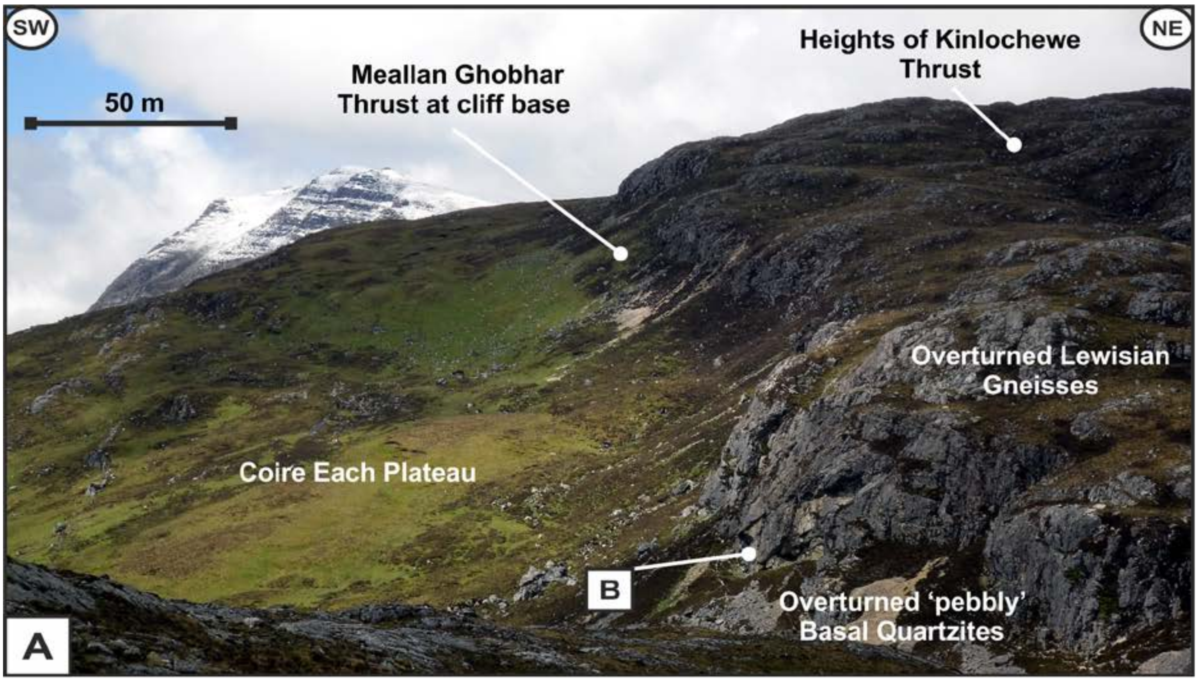


Figure 5.22: (A) Overview of the Coire Each Plateau from the Meallan Ghobhar summit to Bonaid Dhonn incorporating the Coire Each, Meallan Ghobhar and Heights of Kinlochewe thrust sheets. Observations highlighted in text numbered. **(B, C)** Transpressional folding identified within the Meallan Ghobhar Summit highlighting interactions of the Coire Each and Meallan Ghobhar thrust sheets comprising right-way-up Torridonian sandstones and Eriboll Formation quartzites and overturned Eriboll Formation (Basal Quartzites).

Meallan Ghobhar Summit (Coire Each Plateau),
Meallan Ghobhar domain, Heights of Kinlochewe Sector
[NH 0262 6491]



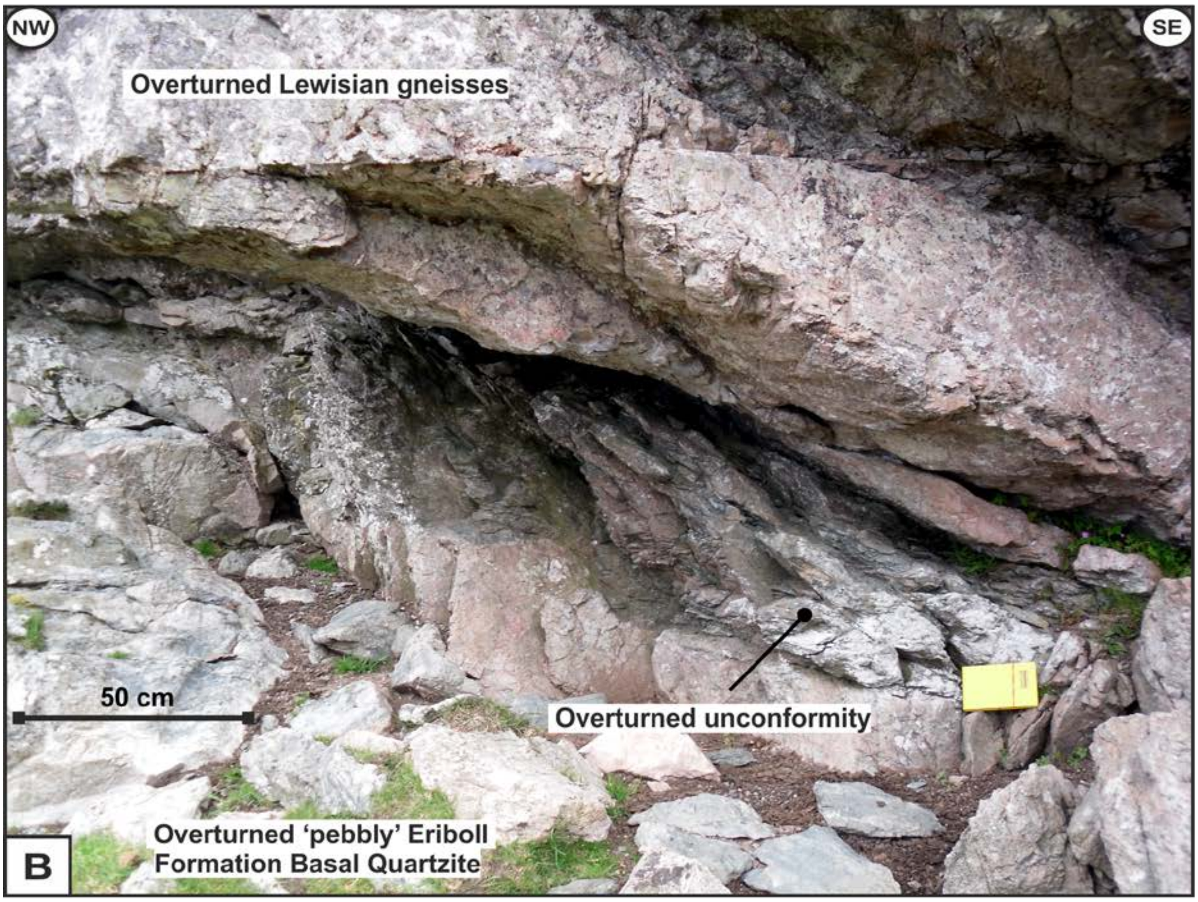
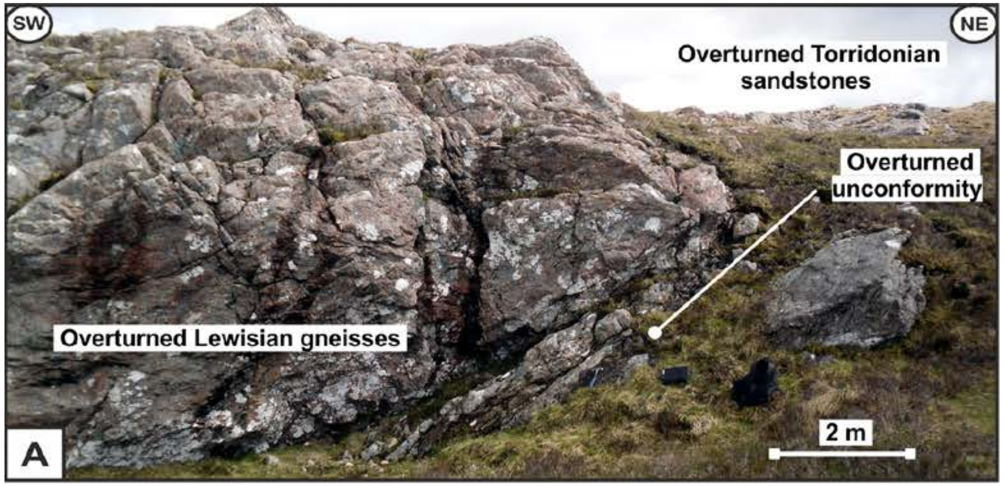


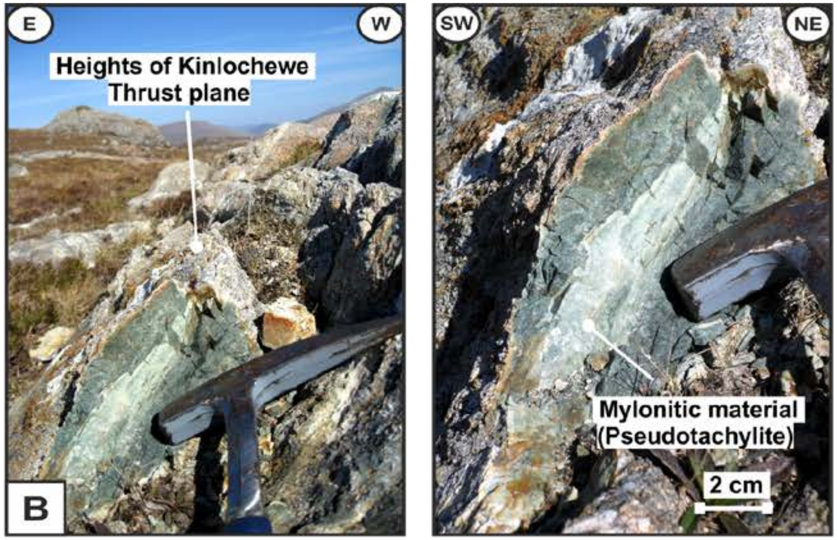
Figure 5.23: (A) Overview of the Coire Each Plateau. Along the Coire Each cliff line, interactions of the Meallan Ghobhar truncating the underlying Coire Each are observed placing overturned Lewisian gneisses and Eriboll Formation 'pebbly' Basal Quartzites over Coire Each and foreland An t-Sron Formation lithologies. Overturned unconformity identified along the base of the Coire Each cliff line **(B)**.

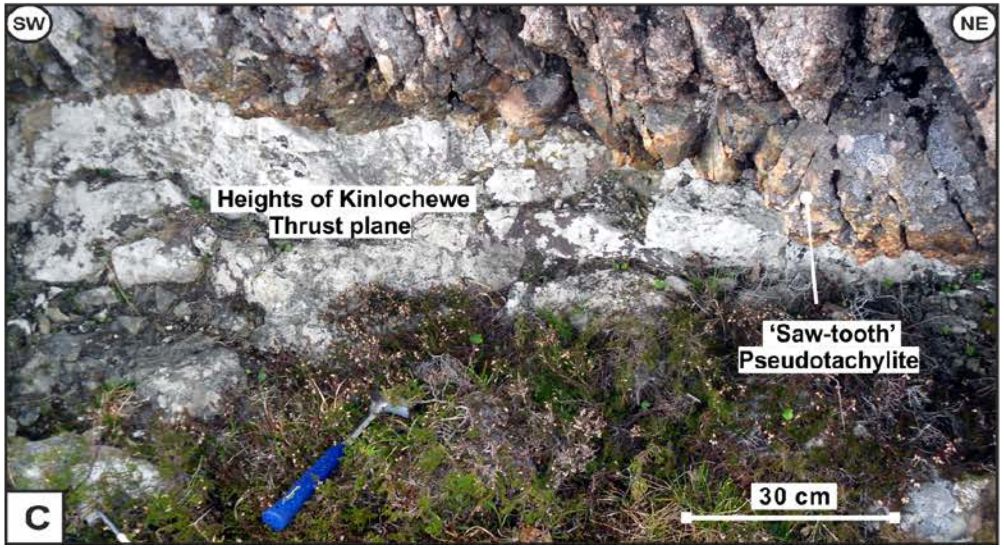
South-eastwards of the Coire Each plateau region, numerous examples of the interaction of the overturned 'double unconformity' can be viewed. These include overturned 'pebbly' Basal Quartzite interactions with overturned Lewisian gneisses [NH 0282 6491] and overturned Lewisian gneisses with overturned Torridonian sandstones [NH 0330 6465] (Figure 5.18a [12]; 5.22a [3]; 5.24a). Thicknesses of the overturned Lewisian gneisses vary laterally along the Heights of Kinlochewe sector from tens of metres (Figure 5.18a [11]) to a maximum of six hundred thirty metres (Figure 5.18a [13]).

Overturned Lewisian gneisses of the Meallan Ghobhar thrust sheet are over-thrust by a different suite of Scourie dyke-containing gneisses (i.e., Heights of Kinlochewe thrust sheet), which are similar in nature to those observed along the base of the Heights of Kinlochewe sector against the Loch Maree Fault (Figure 5.18a [14]). No evidence for Scourie dykes is present within the overturned Lewisian gneisses of the Meallan Ghobhar thrust sheet along the Heights of Kinlochewe sector. Traces of pseudotachylite are identified along the Heights of Kinlochewe Thrust plane which can be mapped for over three kilometres southeast from the Meallan Ghobhar lochens [NH 0342 6487] to Carn an Uillt Ghiuthais [NH 0539 6471] (Figure 5.1a [14, 15]; 5.22a [4]; 5.24b; 5.24c).

The presence of pseudotachylite material indicates the generation of large amounts of heat causing partial melting of the fault-wall rock as a result of brittle movements along the fault plane. Pseudotachylite material thicknesses vary from a couple of centimetres (Figure 5.24b) to large (twenty centimetre) 'saw-tooth' exposures [NH 0345 6488] along the Heights of Kinlochewe Thrust fault-wall (Figure 5.24c). The vast mappable extent of this material indicates that the Heights of Kinlochewe Thrust has undergone considerable displacement along-strike.







Overturned Unconformities/Heights of Kinlochewe Thrust,
Meallan Ghobhar domain,
Heights of Kinlochewe Sector
[NH 0330 6465 and NH 0342 6487 to 0539 6471]

Figure 5.24: (A) Overturned unconformity identified along the Meallan Ghobhar cliff line between overturned Lewisian gneisses and overturned Torridonian sandstones [NH 0330 6465]. Overturned Lewisian gneisses of the Meallan Ghobhar thrust sheet are over-thrust by a different suite of Scourie dyke-containing gneisses (i.e., Heights of Kinlochewe thrust sheet).

(B, C) Traces of pseudotachylite are identified along the Heights of Kinlochewe thrust plane, mapped for over 3 km southeast from the Meallan Ghobhar lochens [NH 0342 6487] to Carn an Uillt Ghiuthais [NH 0539 6471]. Pseudotachylite material thicknesses vary from a couple of centimetres **(B)** to large (20 cm) 'saw-tooth' exposures [NH 0345 6488] along the Heights of Kinlochewe Thrust fault-wall **(C)**.

5.1.4. Heights of Kinlochewe Sector: Cross-strike three-dimensional distribution

Map patterns identified within Figure 5.1a; 5.2b and field observations described within previous sections identify a series of transport-lateral and transport-parallel discontinuities within the Heights of Kinlochewe sector, from the hinterland Glen Bruachaig-Incheril Window domain to the forelandmost Meallan Ghobhar domain. Cross-strike map patterns and cross-sections (located on Figure 4.1; 5.1); indicate a series of northeast-southwest trending cross-strike discontinuities from the Loch Maree Fault to the highest regions of the Heights of Kinlochewe sector. Architectural discontinuities are also identified orientated sub-parallel to regional transport (i.e., 290 / 300°) indicating a distinct forelandward geometrical change from the Glen Bruachaig-Incheril Window domain to the 'Burn of Bones' and Meallan Ghobhar domains. Transport-parallel and transport-lateral discontinuities occur as a result of interactions between the Coire Each, Meallan Ghobhar and Heights of Kinlochewe thrusts and their respective thrust sheets.

Within the Glen Bruachaig-Incheril Window domain, the eponymous structure comprises a window into the underlying Coire Each Thrust Sheet, identifying a bulged duplex dominated by An t-Sron Formation lithologies (i.e., Innis Dhriseach imbricates) and cored by Eriboll Formation (Pipe Rock) units (Figure 5.1a [1]; 5.4; 5.25a [1]; 5.25b [1]). Downward-facing folds within An t-Sron Formation Salterella Grits are identified along the Innis Dhriseach imbricates indicating forelandward propagation within the regional (290 / 300°) transport direction. Downward-facing fold development occurs as a result of bulging within the Window in response to a rise in the forelandward-vergent trajectory of the Coire Each Thrust and differential along-strike thrust propagation within An t-Sron Formation lithologies (i.e., Fucoid Beds and Salterella Grits). Consequently, hinterlandward stacking of An t-Sron Formation thrust imbricates is observed inflating the Window within the Meallan Ghobhar footwall (Figure 5.25a [2]).

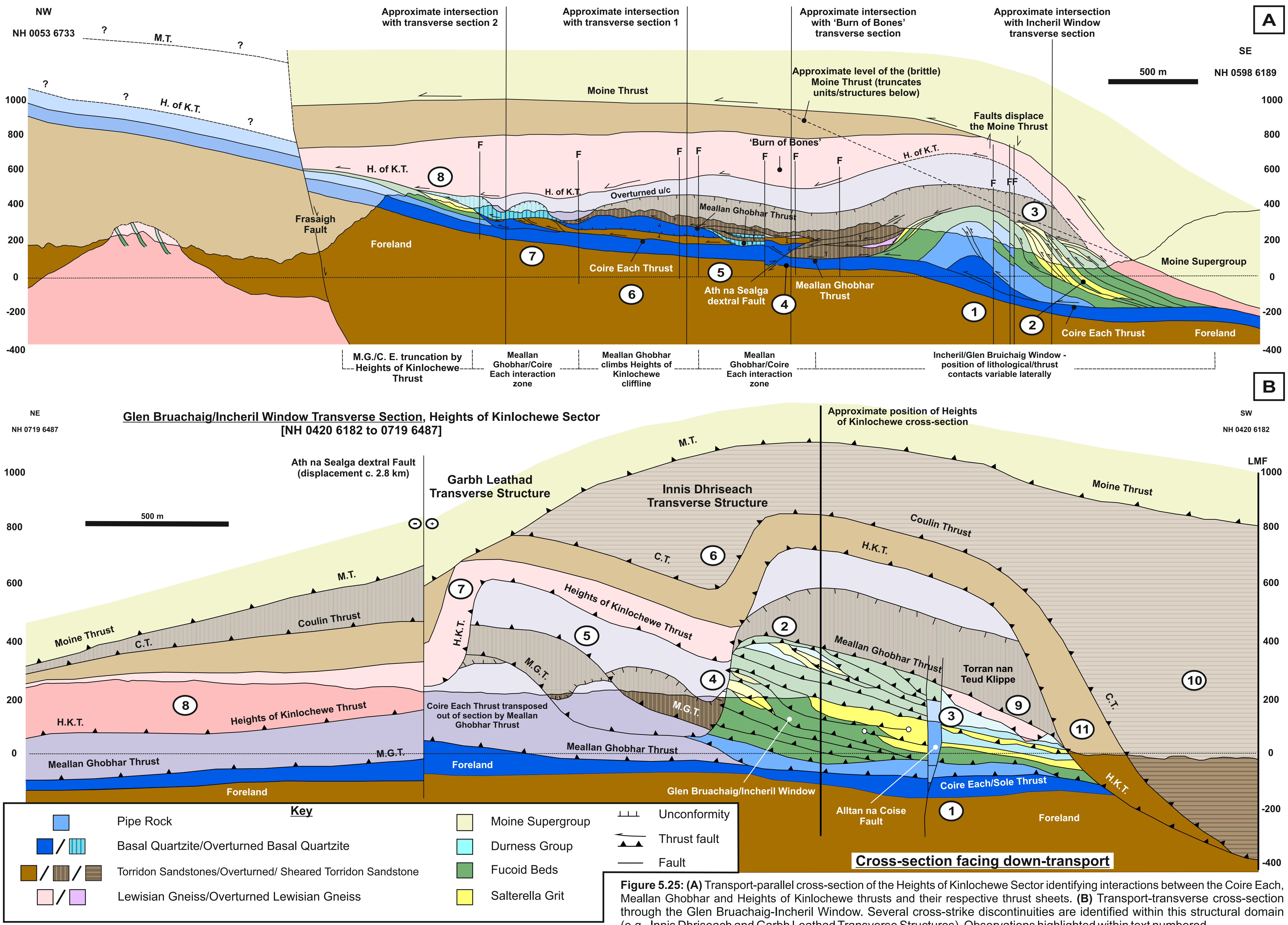


Figure 5.25: (A) Transport-parallel cross-section of the Heights of Kinlochewe Sector identifying interactions between the Coire Each, Meallan Ghobhar and Heights of Kinlochewe thrusts and their respective thrust sheets. **(B)** Transport-transverse cross-section through the Glen Bruachaig-Incheril Window. Several cross-strike discontinuities are identified within this structural domain (e.g., Innis Dhriseach and Garbh Leathad Transverse Structures). Observations highlighted within text numbered.

From southwest to northeast, lateral variations within the Glen Bruachaig-Incheril Window are observed highlighting along-strike discontinuities within the Coire Each Thrust Sheet. Thrust imbricates within north-eastern sections of the Window stratigraphically cut-up from An t-Sron Formation Fucoid Beds to Durness Group limestones and are truncated by the overlying Meallan Ghobhar roof-thrust; indicating that doming of the Window is synchronous with movements along the Meallan Ghobhar Thrust, truncating units within its footwall (Figure 5.25b [2]). Conversely, south-western portions of the window are dropped by the transport sub-parallel Alltan na Coise Fault, preserving Durness Group limestones (Figure 5.25b [3]). The Alltan na Coise Fault therefore identifies both pre-thrust movements, dropping the south-western side of the Window, and later phases of strike-slip fault movements entraining Eriboll Formation Pipe Rock units from the Window core. Later strike-slip developments along the Alltan na Coise Fault also displace higher thrust sheets.

Along-strike and cross-strike variations in imbricate style are also observed within the Glen Bruachaig-Incheril Window. Imbricate developments within north-eastern sections of the Window far outweigh production within the south-western sections resulting in a doubling of the Window thickness (Figure 5.25b [2, 3]). It is suggested that the Alltan na Coise Fault and the north-eastern termination of the Window act as sidewalls encouraging further thrust nucleations within this sector of the Window (Figure 5.25b [3, 4]). Thrust nucleations are assisted by a more incompetent An t-Sron Formation package presented to thrusting, comparable to south-western portions of the Window, due to pre-thrust movements along the Alltan na Coise Fault. A cross-strike discontinuity is therefore identified within the Coire Each Thrust Sheet within the Glen Bruachaig-Incheril Window.

Along the north-eastern termination of the Window, along-strike variations within the overlying Meallan Ghobhar Thrust Sheet are also identified. The Meallan Ghobhar Thrust drastically cuts down section within map-view from carrying overturned sequences of Torridonian sandstones and Lewisian gneisses within the Glen Bruachaig-Incheril Window roof-thrust (Figure 5.25a [3]; 5.25b [2]), to thrust imbricates comprising folded Meallan Ghobhar lithologies along the Garbh Leathad hillside [NH 0585 6349] (Figure 5.25b [5]). Evidence supporting observations are identified within map-view by overturned unconformities appearing 'right-way-up' within varying thrust imbricates, as well as, truncations of the Glen Bruachaig-Incheril Window along the Allt na h-Innse Drisich stream [NH 0553 6316] (Figure 5.1a [9, 10]). Map-patterns indicate a cross-strike discontinuity in which the position of overturned lithologies 'back-step' across the Glen Bruachaig-Incheril Window.

Structurally above these units, the overlying Heights of Kinlochewe Thrust also drastically cuts down section stratigraphically and topographically, cutting out Torridonian sandstones identified within the south-western sections of the Window (Figure 5.1a [5]), until they are identified along the Garbh Leathad hillside north of the Ath na Sealga Fault (Figure 5.1a [16]). This further pronounces cross-strike discontinuities identified within the underlying Meallan Ghobhar and Coire Each thrust sheets, creating a sidewall along which imbricates within the Coire Each hanging-wall terminate. The structurally higher Coulin Thrust Sheet is also truncated across this structure and is not identified within map-view until north of the Ath na Sealga Fault near the Leckie Farm [NH 0968 6451]. These series of cross-strike discontinuities identify the Innis Dhriseach Transverse Structure (IDTS), which bounds the north-eastern edge of the Glen Bruachaig-Incheril Window and offsets overlying higher thrust sheets (Figure 5.25b [6]). Map-patterns suggest that development of the Innis Dhriseach Transverse Structure incorporates pre-, syn-, and post-thrusting kinematic elements producing a series of cross-strike discontinuities.

Northeast across Garbh Leathad, imbricates of the Meallan Ghobhar are truncated by the Heights of Kinlochewe Thrust carrying right-way-up Lewisian gneisses until only Lewisian gneisses of the Heights of Kinlochewe Thrust Sheet are observed north of the Ath na Sealga Fault [NH 0647 6360] (Figure 5.1a [17]; 5.25b [7, 8]). To accommodate such a drastic along-strike change in stratigraphical units within similar topographical regions, a further sidewall within the Heights of Kinlochewe Thrust Sheet is suggested (i.e., the Garbh Leathad Transverse Structure). This structure is subsequently truncated by later brittle strike-slip faulting of the Ath na Sealga Fault dextrally transporting material c. 2.8 kilometres up to and including the Moine Thrust Sheet (Figure 5.1a [7b]; 5.25b [7]).

Lewisian gneisses of the Heights of Kinlochewe, mapped for over three kilometres across the Heights of Kinlochewe from Garbh Leathad (Figure 5.1a [16]) to the Sgurr Beinn a' Mhùinidh / Meallan Ghobhar hillside [NH 0273 6523] (Figure 5.1a [14]), link with those identified along the Creag Ruadh Sidewall, along a southwest-dipping thrust which can be mapped for over two kilometres along the Kinlochewe river. This southwest-dipping thrust places Lewisian gneisses over right-way-up stratigraphy of the Coire Each Thrust Sheet, overturned stratigraphy of the Meallan Ghobhar Thrust Sheet and the Glen Bruachaig-Incheril Window (Figure 5.1a [12, 13]). Lewisian gneisses within the Abhainn Bruachaig valley on the southeast of the Glen Bruachaig-Incheril Window and the Torran nan Teud Klippe also comprise part of this higher thrust sheet, connecting through the west-southwest-east-northeast trending Ath na Sealga Fault to those within Garbh Leathad (Figure 5.1a [1, 6, 7b]; 5.25b [7, 8, 9]).

A steep lateral ramp is therefore identified within the Heights of Kinlochewe Thrust Sheet along the north-eastern side of the Loch Maree Fault (i.e., Creag Ruadh Lateral Ramp) along which the Heights of Kinlochewe Thrust Sheet down-warps south-westwards, highlighted by horizontal Scourie dykes within the Creag Ruadh hillside (Figure 5.1a [12]; 5.6). The Glen Bruachaig-Incheril Window is suggested to be a separate entity within the footwall of the Creag Ruadh lateral ramp, and not laterally continuous beyond the Innis Dhriseach Transverse Structure (IDTS). Map-patterns indicate that later deformation phases within the Glen Bruachaig / Incheril Window domain are dominated by brittle process along the Ath na Sealga dextral fault and the Moine Thrust, which truncates underlying thrust sheets to the roof of the Window (Figure 5.25a [3]).

Forelandward of the Glen Bruachaig-Incheril Window, the Meallan Ghobhar roof-thrust is observed dominating the 'Burn of Bones' domain (Figure 5.1a [11]). Within this domain, overturned Torridonian sandstones are observed steepening north-westwards from 30° to 80° within the transport direction towards the Ath na Sealga Fault. Thrust imbricates highlight complex thrust geometries and overturned unconformities between overturned sequences of Torridonian sandstones, Lewisian gneisses and Eriboll Formation Basal Quartzites (Figure 5.1a [8]; 5.16; 5.17), which are further complicated by interactions with the later Ath na Sealga dextral fault system (Figure 5.1a [8]; 5.25b [4]).

Within the 'Burn of Bones' interactions of the Coire Each and Meallan Ghobhar thrusts are identified, indicating that the Coire Each Thrust carries right-way-up sequences of Eriboll Formation Basal Quartzites and Torridonian sandstones which are truncated by the higher Meallan Ghobhar Thrust Sheet two hundred metres above the loch level (Figure 5.7a [6, 7, 8, 9]). Therefore, the floor thrust to the Glen Bruachaig-Incheril Window (i.e., Coire Each Thrust) must link via the Meallan Ghobhar Thrust to the ramp west of the 'Burn of Bones' which cuts through the Coire Each Thrust Sheet (Figure 5.7a [5]; 5.25a [5]). Evidence of transpressional down-warping is observed along these thrusts similar to those within the Heights of Kinlochewe Thrust Sheet at Creag Ruadh indicating a system undergoing lateral compression and / or vertical loading from the overlying Meallan Ghobhar Thrust Sheet, all of which are subsequently displaced by dextral strike-slip faulting (Figure 5.12).

Along the Heights of Kinlochewe cliff line, the Coire Each Thrust, carrying a slab of right-way-up Torridonian sandstones and Eriboll Formation Basal Quartzites, maintains its thrust trajectory along the Meallan Ghobhar hillside (i.e., two hundred metres above loch level; Figure 5.18a [5]). Conversely, the Meallan Ghobhar rapidly cuts up the hillside forelandward into the Meallan Ghobhar summit, stratigraphically cutting up-section from overturned Torridonian sandstones to overturned Basal Quartzites, truncating earlier fold structures within the underlying Coire Each Thrust Sheet (Figure 5.18a [6]; 5.21a; 5.25a [6]). As the Coire Each Thrust climbs the Meallan Ghobhar cliff line, interactions with the overlying down-cutting Meallan Ghobhar Thrust cause a bifurcation of the Coire Each along the ‘Goat-path cliff’, the higher carrying Torridonian sandstones over the lower Eriboll Formation Basal Quartzites (Figure 5.18a [8]; 5.19b; 5.21a; 5.25a [7]).

Along the Coire Each Plateau, the Coire Each Thrust is completely truncated by the overlying Meallan Ghobhar Thrust (Figure 5.18a [10]), which is itself truncated along the Sgurr Beinn a’ Mhùinidh by the overlying Heights of Kinlochewe Thrust Sheet of right-way-up Lewisian gneisses (Figure 5.25a [8]). Thrust sequences indicate that forelandward-propagation of the Coire Each, Meallan Ghobhar and Heights of Kinlochewe develop out-of-sequence either as a result of thrust interactions stagnating forelandward thrust propagation or resulting from oscillatory thrust processes along the Heights of Kinlochewe sector.

5.1.5. Heights of Kinlochewe Sector: Summary

Within the Heights of Kinlochewe Sector, fault network analyses and field observations allow the following pertinent characteristics to be identified within Table 5.1. Characteristics highlight a distinct cross-strike change from the southern wall of the Loch Maree Transverse Zone (LMTZ), (i.e., Beinn Eighe and Meall a' Ghiubhais sectors), to the northern wall of the LMTZ (i.e., Heights of Kinlochewe Sector). Cross-strike discontinuities and cross-strike linkages are identified within the following sections.

Heights of Kinlochewe Sector: Summary findings	
Region	**Observation highlights**
Glen Bruachaig/Incheril Window domain	• Dominated by Glen Bruachaig-Incheril Window, comprising right-way-up sequences of An t-Sron Formation imbricates, cored by Eriboll Formation Pipe Rock lithologies (i.e., Coire Each Thrust Sheet). Thrust imbricates within the Window stratigraphically cut-up section northeastwards from An t-Sron Formation Fucoid Beds to Durness Group limestones. Imbricates truncated by overlying Meallan Ghobhar roof-thrust along northeastern Window edge, indicating Window inflation during synchronous roof-thrust movements. • Downward-facing folds identified indicating forelandward-propagation within regional (290 / 300°) transport direction. Result from rise in forelandward-vergent trajectory of underlying Coire Each Thrust, causing a hinterlandward stacking of An t-Sron Formation imbricates bulging the Window. South-western portions of Window preserve Durness Group limestones, indicating a south-westwards drop along the Alltan na Coise Fault. Alltan na Coise Fault entrains Eriboll Formation Pipe Rock lithologies from core region, indicating later strike-slip movements whilst acting as a sidewall for thrust imbricate nucleation within northeastern Window sections. • Overlying roof-thrust (i.e., Meallan Ghobhar Thrust Sheet) comprises overturned Torridonian sandstones and Lewisian gneisses. Numerous examples of overturned unconformity identified. Meallan Ghobhar roof-thrust drastically cuts down section north-eastwards from overturned Torridonian sandstone and Lewisian gneiss sequences to thrust imbricates containing folded Meallan Ghobhar units. Location of overturned lithologies 'back-stepped' across Window identifying a cross-strike discontinuity (i.e., Innes Dhriseach Transverse Structure [IDTS]). • Heights of Kinlochewe Thrust carrying right-way-up, Scourie dyke containing, Lewisian gneisses overlie the Meallan Ghobhar. Units drastically cut down section stratigraphically and topographically cutting out Torridonian sandstones northeast across the Window domain (i.e., across IDTS). Further truncation of underlying Meallan Ghobhar imbricates across Garbh Leathad indicates a second cross-strike discontinuity/sidewall (i.e., Garbh Leathad Transverse Structure [GLTS]). • Lewisian gneisses identified with Abhainn Bruachaig valley, Torran nan Teud Klippe and along a southwest-dipping thrust along the Creag Ruadh hillside, also comprise the Heights of Kinlochewe Thrust Sheet. Down-warping of the Heights of Kinlochewe Thrust along Creag Ruadh, highlighted by horizontal Scourie dykes, indicates a steep lateral ramp sub-parallel to the Loch Maree Fault (i.e., Creag Ruadh Lateral Ramp), confining underlying Meallan Ghobhar / Coire Each thrust sheets. Glen Bruachaig-Incheril Window suggested to be a separate entity within the footwall of Creag Ruadh Lateral Ramp terminating along the IDTS. • Coulin Thrust Sheet comprising sheared Torridonian sandstones, identified along southwestern sections of the Window. Not observed laterally along-strike until north of the Ath na Sealga Fault within the footwall of the Moine Thrust east of the Leckie Farm. Units truncated and 'back-stepped' across the IDTS and GLTS. Units of the Coulin thrust sheet are overridden by the Moine thrust sheet. Moine Thrust highlights later brittle movements which truncate underlying thrust sheets to the top of the Glen Bruachaig-Incheril Window. • Strike-slip movements occur as one of the last phases of development within the Heights of Kinlochewe sector. Ath na Sealga dextral fault truncates the Glen Bruachaig-Incheril Window, the GLTS, and all overlying thrust sheets up to, and including, the Moine Thrust by c. 2.8 km.
Glen Bruachaig/Incheril Window: **Cross-strike discontinuities**	• Series of cross-strike discontinuities observed: (1) Coire Each Thrust Sheet: Lateral variations identified within Glen Bruachaig-Incheril Window separated by the Alltan na Coise Fault. Northwestern Window sections are thickened more than southwestern portions due to a more incompetent stratigraphical package presented to thrusting (i.e., An t-Sron Formation lithologies versus Durness Group limestones). (2) Innes Dhriseach Transverse Structure: Series of along-strike variations within various thrust sheets including; along-strike termination of Coire Each Thrust Sheet imbricates against the IDTS, down-cutting of the Meallan Ghobhar roof-thrust into Meallan Ghobhar Thrust imbricates truncating the Window roof; down-cutting of the overlying Heights of Kinlochewe, removing Torridonian sandstones. Heights of Kinlochewe and Coulin thrust sheets are also 'back-stepped' across this structure. Higher thrust sheets amplify along-strike variations. (3) Garbh Leathad Transverse Structure: Heights of Kinlochewe Thrust Sheet truncates underlying Meallan Ghobhar imbricates highlighting a second sidewall. Sidewall truncated by later dextral strike-slip movements along the Ath na Sealga Fault.

Table 5.1: Summary findings within the Heights of Kinlochewe Sector. Observation highlights within the Glen Bruachaig/Incheril Window domain are identified, whilst cross-strike discontinuities are also summarised.

Heights of Kinlochewe Sector: Summary findings

Region	Observation highlights
'Burn of Bones' domain	• Domain comprising an 800 m river-cutting, dominated by complex thrust geometries incorporating interactions of the Coire Each, Meallan Ghobhar and Heights of Kinlochewe thrust sheets. Thrust imbricates dominated by overturned lithologies of the Meallan Ghobhar Thrust Sheet including Torridonian sandstones, Lewisian gneisses and Eriboll Formation Basal Quartzites. Many overturned unconformities identified. Thrust geometries complicated by later dextral strike-slip movements along Ath na Sealga Fault, highlighted by fault cut-off points. Along the 'Burn of Bones' lower slopes, continuations of Creag Ruadh Sidewall / Lateral Ramp, comprising right-way-up Lewisian gneisses (Heights of Kinlochewe thrust sheet) observed lying on a southwest-dipping thrust producing hanging-wall anticlines. Converse to the Creag Ruadh hillside, Scourie dykes show little internal deformation, retaining their sub-vertical profile. • Coire Each and Meallan Ghobhar Thrust Sheet interactions identified. Coire Each Thrust carries right-way-up Torridonian sandstones and Eriboll Formation Basal Quartzites. An t-Sron Formation dominant Windows observed into the underlying Coire Each footwall along river baseline. Overlying Meallan Ghobhar is observed truncating the underlying Coire Each Thrust Sheet 200 m above loch level within Allt Chnàimhean hillside. Transpressional (top-to-southwest [250°]) down-warping identified within these thrust sheets, producing large (3 m+) hanging-wall anticlines orientated sub-parallel to the Heights of Kinlochewe, resulting from lateral compression and / or vertical loading from overlying thrust sheets. Evidence for forelandward-propagation identified within regional (290 / 300°) transport direction. Hanging-wall anticlines along Coire Each Thrust splays truncate underlying thrusts indicating plunging out-of-sequence thrusting. Original 'Basal Quartzite Keels' of Peach et al., (1907) identified as a sequence of overturned Torridonian sandstones and Eriboll Formation Basal Quartzites thrust over an overturned sequence of Lewisian gneisses and Torridonian sandstones.
Meallan Ghobhar domain	• Dominated by Meallan Ghobhar crags (468 m) along which complex interactions between the Coire Each and Meallan Ghobhar are identified, producing numerous branch-lines. Underlying these thrust sheets, lower slopes of Meallan Ghobhar sector from Bac 'an t-Sniomha to Bonaid Dhonn dominated by undeformed, southeast-dipping foreland lithologies, comprising Torridonian sandstones (300 m), Eriboll Formation quartzites (200 m) and An t-Sron Formation units (30 m). Creag Ruadh Sidewall identified and separated from Meallan Ghobhar cliff by several vertical faults, forming part of the Loch Maree Fault (LMF) system (i.e., Torr an Eoin Splay). Interactions of LMF identified in form of large slickenside evidence indicating sinistral and dextral fault movements. • Coire Each Thrust Sheet traced southeast to 'Burn of Bones' domain where it is truncated by Meallan Ghobhar Thrust. Large folds within Coire Each Thrust Sheet truncated by Meallan Ghobhar as it climbs the Meallan Ghobhar hillside, indicating out-of-sequence / oscillatory thrusting. Transpressional and regional transport directions identified along hillside. Meallan Ghobhar Thrust climbs its eponymous hillside carrying overturned Torridonian sandstones into overturned sequences of Eriboll Formation 'pebbly' Basal Quartzites indicating a rise in stratigraphical detachment. Along the Coire Each plateau, Coire Each Thrust completely truncated by overlying Meallan Ghobhar Thrust. Overturned Lewisian gneisses and 'pebbly' Eriboll Formation Basal Quartzite unconformity identified. Heights of Kinlochewe Thrust mapped for 3 km along highest reaches of the Heights of Kinlochewe domain via pseudotachylite traces.
'Burn of Bones' and Meallan Ghobhar domains: **Cross-strike discontinuities**	• Two senses of cross-strike discontinuity observed: (1) Northeast-southwest: Along-strike truncation of underlying thrust sheets as a result of transpressional down-warping along the Coire Each, Meallan Ghobhar and the overlying Heights of Kinlochewe thrust sheets. Transpressional deformation, resulting from lateral compression and / or vertical loading, assists forelandward development of out-of-sequence / oscillatory thrusting. Development of Creag Ruadh Lateral Ramp / Sidewall from Glen Bruachaig-Incheril Window domain to Meallan Ghobhar domain. (2) Northwest-southeast: Transport-parallel structural style change identified between Glen Bruachaig/Incheril Window, 'Burn of Bones' and Meallan Ghobhar domains. Forelandward-propagation highlights complex interactions between the Coire Each, Meallan Ghobhar and Heights of Kinlochewe thrust sheets, resulting from out-of-sequence / oscillatory thrusting, interactions of differing rheological behaviours within individual thrust sheets and complex interactions with later strike-slip faults (i.e., Ath na Sealga Fault).

Table 5.1...cont: Summary findings within the Heights of Kinlochewe Sector. Observation highlights within the 'Burn of Bones' and Meallan Ghobhar domains identified, whilst cross-strike discontinuities also summarised.

5.2. Loch Maree Transverse Zone (LMTZ) and its cross-strike linkages

Within the southern sidewall of the Loch Maree Transverse Zone (LMTZ), several cross-strike discontinuities are identified. These define a cross-strike transition from a one and a half kilometre 'slab-like' structural package, comprising Torridonian sandstones and Eriboll Formation lithologies along the Beinn Eighe southern wall, to a two hundred metre Eriboll Formation to An t-Sron Formation 'thin-flap' geometry along the Cadh' a' Mheanbh-chruidh / Carraig Alltan Mhic Eoghainn cliff line within the Meall a' Ghiubhais sector. Transverse structures identified within this southern wall include the Beinn Eighe Lateral Ramp and the Leathad Buidhe / Doire Dharaich Transverse System. Conversely, within the northern wall of the Loch Maree Transverse Zone, drastic structural changes incorporating interactions of right-way-up, overturned and basement lithologies are observed. Cross-strike discontinuities are identified within the most hinterland domains (i.e., Innis Dhriseach and Garbh Leathad Transverse Structures). A cross-strike change from a fold-thrust dominant southern wall to a thick-skinned, thrust dominant northern wall is therefore evident.

The following sections identify thrust lateral continuity and the forelandward development of the Loch Maree Transverse Zone and its cross-strike discontinuities. Cross-strike linkages between the southern and northern walls are highlighted (Table 5.2), whilst transport-lateral cross-sections (located within Figure 4.1) are used to visualise cross-strike responses to identified transverse structures and their forelandward expression (Figure 5.26; 5.27). Findings are used to create a pre-thrust template for the Loch Maree Transverse Zone.

Thrust/Structural Package	Beinn Eighe Sector (South)	Beinn Eighe Sector (North)/Transition Zone	Meall a' Ghiubhais Sector	Loch Maree Fault (LMF)	Heights of Kinlochewe Sector
Moine Thrust (Psammites/Semi-pellites)	Crenulation cleavage - support top-to-NW (290/300°) regional transport	Laterally continuous	Laterally continuous	**Displaced 1.7 km (min)**	Laterally continuous - displaced by Alltan na Coise and Ath na Sealga Faults (c. 2.8 km). Last movements indicate 'brittle' Moine Thrust truncates underlying thrust sheets to Window roof-thrust
Coulin Thrust (Sheared Torridonian sandstones/ Lewisian gneisses)	1 km to 800 m thick (map-view) Sheath folds - support top-to-NW (290/300°) regional transport	700 m thick (map-view) Coulin truncates underlying Kinlochewe southwards (1.26 km to 120-180 m) indicating late phase Coulin movement	500 m to 300 m thick (map-view) - Northwards thinning	**Displaced 1 km (min)**	Coulin not laterally continuous - 'back-stepped' across IDTS and GLTS. Displaced by Alltan na Coise Fault (Unknown distance) and Ath na Sealga Fault (c. 2.8 km)
Kinlochewe Thrust (RWU, undeformed Torridonian sandstones)	180-120 m thick (map-view) (Truncation by overlying Coulin)	1.26 km thick in Meall a' Ghiubhais sector - 700 m thick (map-view) within transition zone (Truncation by overlying Coulin)	**500 m Kinlochewe/Sole Thrust interaction zone identified. Kinlochewe down-warping/loading underlying strata. Kinlochewe Thrust 200 m lower on LMF side (deflection during down-cutting). Out-of-sequence development create Klippe (i.e., Bhanabhaig Klippe)**	**Kinlochewe acts as roof-thrust to footwall imbricates** / **Not laterally continuous - Coire Each closest equivalent within northern wall** / **Creag Ruadh Lateral Ramp/Sidewall along LMF northern wall**	**Heights of Kinlochewe Thrust:** • **Back-stepped over Window/IDTS. Drastically cuts-down stratigraphically, cutting out Torridonian units over IDTS. Sidewall identified (i.e., GLTS) truncating Meallan Ghobhar imbricates.** • **Heights of Kinlochewe thrust sheet down-warps along LMF at Creag Ruadh. Steep lateral ramp (Creag Ruadh Lateral Ramp) confining all underlying thrust sheets. No linkages into southern wall.**
Meallan na Circe-fraoich Thrust (Kinlochewe footwall imbricates)	Eriboll Formation dominant, steeply dipping units (40-55°). Large hanging-wall synclines observed between 400 m spaced thrusts. Higher thrust detachment indicated.	Thick Eriboll Basal Quartzite dominant thrust sheets. Pre-thrust folding observed along Meall a' Ghiubhas. Out-of-sequence thrust phase observed. Numerous bifurcations observed - LSTS/DDTS interactions	Raise of detachment into Eriboll Formation Pipe Rock indicating flat-on-flat geometry within WNW-NW-vergent (290/300°) system. Thrust spacing 200-400 m. Units shallow dipping (20-30°). Broad hanging-wall anticlines observed	**Not laterally continuous**	
Coire Domhain Thrust (Kinlochewe footwall imbricates)	Eriboll Formation dominant, steeply dipping units (40-55°). Higher thrust detachment indicated. Numerous hanging-wall splays observed over Beinn Eighe - Beinn Eighe Lateral Ramp interactions	Eriboll Formation dominant thrust sheets indicate numerous hanging-wall splays across Beinn Eighe terminate along Meall a' Ghiubhas hillside - LBTS interactions identified.	**Single dominant thrust identified interacting with pre-thrust folds at Doire Dharaich - Ramp-on-ramp geometries and lateral shortening/transpression observed. DDTS interactions identified.**	**Not laterally continuous**	**Meallan Ghobhar Thrust:** • **Window roof-thrust. Back-stepped and drastically cuts down into folded imbricate sequences across IDTS. Subsequently truncated by higher Heights of Kinlochewe thrust sheet along GLTS.** • **Complex interactions of thrust imbricates/overturned unconformities/later dextral faulting (i.e., Ath na Sealga Fault) observed.** • **Ramp up Meallan Ghobhar hillside truncating Coire Each fold structures (out-of-sequence thrusting).**
Sgurr na Conghair Thrust (Kinlochewe footwall imbricates)	Eriboll Formation dominant, steeply dipping units (40-55°). Start of ramp-on-ramp geometries identified. Samples Torridonian sandstones within southern wall but cut out across Beinn Eighe. Higher thrust detachment indicated.	Eriboll Formation (Basal Quatzite) dominant units. Numerous thrust bifurcations identified forelandward of the Meall a' Ghiubhais hillside - LBTS interactions identified.	**Single dominant thrust identified interacting with pre-thrust folds at Doire Dharaich developing into shallow imbricates. Ramp-on-ramp geometries and lateral shortening/transpression observed. DDTS interactions identified.**	**Not laterally continuous**	
Creag Dhubh Thrust (Kinlochewe footwall imbricates)	Seven hanging-wall splays stratigraphically cut-up section from Torridonian sandstones to Eriboll Formation lithologies (i.e., Toll Ban/Creag Dhudh imbricates). Units back-steepened (43-58°). Ramp-on-ramp geometries observed.	**Creag Dhubh develops northwards into one dominant thrust branching off Toll Ban (interaction with LBTS).** **Out-of-sequence/oscillatory thrusting observed along Toll Ban Thrust. Overally forelandward-propagation (290/300°) observed.** **Torridonian sandstones decrease laterally to 250-150 m observed along Leathad Buidhe on Toll Ban and along the Coire an Laoigh Thrust (interactions with LBTS).** **Merges along-strike to form Toll Ban/Coire an Laoigh interaction zone (4 thick thrust sheet splays comprising 100-200 m Torridon sandstone + 200 m Eriboll Formation)**	**Not laterally continuous.**	**Not laterally continuous**	**Coire Each Thrust:** • **Window developed in Coire Each thrust sheet. Alltan na Coise Fault divides window, acts as sidewall. IDTS acts as north-eastern sidewall. Window inflated by hinterland imbricate stacking bulging structure and overlying thrust sheets. Window separate entity within Creag Ruadh Lateral Ramp footwall.** • **Develops forelandward into 'Burn of Bones' highlighting transpressional elements (250°). Climbs Meallan Ghobhar cliff where truncated by Meallan Ghobhar thrust sheet.**
Toll Ban Thrust (Kinlochewe footwall imbricates)	Dominant thrust. Slab like geometry comprising Torridonian and Eriboll Formation units. Cuts out Torridonian sandstones within southern wall along Beinn Eighe - Beinn Eighe Lateral Ramp interactions. Two detachments identified.		**Toll Ban/Corie an Laoigh Splay system - form shallow, stacked imbricates indicating a bulging of the thrust front.** **Dominant 500 m long ramp identified (Toll Ban/Coire an Laoigh Ramp).** **Simultaneous, out-of-sequence and oscillatory thrusting phases observed within development.**	**Not laterally continuous**	
Coire an Laoigh Thrust (Kinlochewe footwall imbricates)	Dominant 1 km thick Torridonian sequence identified within hanging-wall - Beinn Eighe Lateral Ramp southern wall. Interacts with Sole Thrust southwards.			**Not laterally continuous**	**Cross-strike Discontinuities:** • Alltan na Coise Fault - divides Coire Each thrust sheet within Window. • Innis Dhriseach Transverse Structure (IDTS) - Window bound on north-east. • Garbh Leathad Transverse Structure (GLTS) - sidewall developed along Heights of Kinlochewe thrust sheet, truncating underlying Meallan Ghobhar imbricates. Truncated by later Ath na Sealga Fault. • Transpressional development along LMF northern wall within Coire Each, Meallan Ghobhar and Heights of Kinlochewe thrust sheets.
Sole Thrust Zone	Two detachments observed - higher detachment containing only Eriboll Formation lithologies, lower within Torridonian sandstones. Sole Thrust Zone composed of diffuse zone of thrust splays off Coire an Laoigh Thrust (shortcut thrusts).	Two detachments observed - higher containing Eriboll Formation, lower within Torridonian sandstones (Separation between two decreasing laterally). Bulging of An t-Sron Formation units identified within Kinlochewe/Sole Thrust interaction zone.	**One detachment along Eriboll Formation/ Torridonian interface - No Torridonian sandstones within thrust system. Dominant ramp identified (Carraig Alltan Mhic Eoghainn). Interactions with Kinlochewe roof-thrust observed (see Kinlochewe Thrust above).**	**Sole Thrust replaced by Coire Each within northern wall**	
Cross-strike Discontinuities (CSDs)	• 1.5 km to 800 m 'slab-like' Torridonian sandstone and Eriboll Formation structural package. • Beinn Eighe Lateral Ramp identified.	• 800 - 400 m Torridonian sandstone/ Eriboll Formation structural package. Torridonian reduced to 300 m in northern wall, 100-200 m in transition zone. • Leathad Buidhe Transverse Structure (LBTS) identified running at 280°.	• 400 m to 200 m 'thin flap' Eriboll Formation structural package - No Torridonian sandstones. • Doire Dharaich Transverse Structure (DDTS) identified running at 290°. • Change of Sole Thrust style and two dominant ramps identified.		

Table 5.2: Cross-strike linkages within Loch Maree Transverse Zone (LMTZ). Colour-coding provided to highlight cumulative number of transport-parallel/transport-lateral discontinuities identified. Key provided below.

1 Cross-strike Discontinuity | 2 Cross-strike Discontinuities | 3 Cross-strike Discontinuities | 4+ Cross-strike Discontinuities

5.2.1. Cross-strike linkages within the LMTZ southern and northern walls

Although the Moine Thrust within the southern and northern walls of the Loch Maree Transverse Zone (LMTZ) is laterally continuous placing Moine Supergroup lithologies onto sheared Torridonian sandstones of the Coulin Thrust Sheet, several minor discontinuities are identified along-strike. Within the Loch Maree Transverse Zone hinterland, the Moine Thrust is identified five hundred metres above sea-level, three hundred metres lower than its equivalent within the Loch Maree Fault (LMF) northern wall, both directly along-strike and across the Glen Bruachaig-Incheril Window domain (Figure 5.25b; 5.26a [1, 2]).

Although the Loch Maree Fault (LMF) identifies both sinistral and dextral movements during its evolution, with last major movement indicating dextral vergence, this structure has only minimal impact on its cross-strike development. Along the Loch Maree Fault, the Moine Thrust is displaced by a minimum of 1.7 kilometres into the Abhainn Bruachaig valley. This does not however, explain the apparent southward drop of the Moine Thrust. This research suggests that this apparent drop is a combination of along-strike thinning of the structural packages within the southern wall lowering the relative level of the Moine Thrust (Figure 5.26a [1]), and a rapid along-strike increase in thrust sheet bulging within the northern wall of the Loch Maree Transverse Zone increasing the relative Moine Thrust height (Figure 5.26a [2]). The height of the Moine Thrust increases south-westwards to over one kilometre above sea-level within the Beinn Eighe Massif region. This is a result of the southward bulging of thrust imbricates within the Kinlochewe footwall during Achnashellach Culmination development, further highlighting this cross-strike disparity (Figure 5.26a [3]).

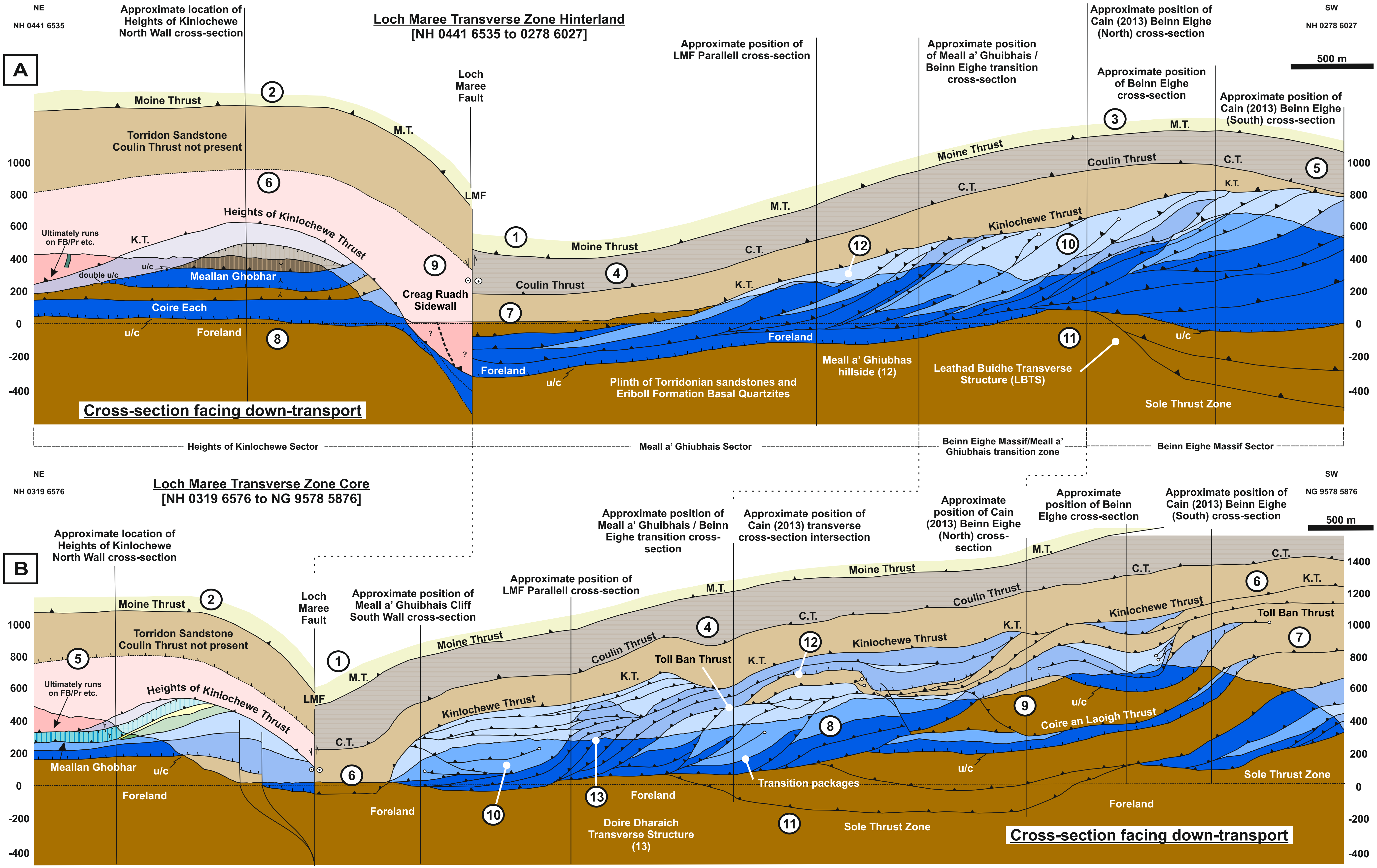


Figure 5.26: (A) Transport-transverse cross-section through the hinterland of the Loch Maree Transverse Zone (LMTZ) southern wall into the centre of the LMTZ northern wall. Observations and cross-strike discontinuities highlighted within text numbered. **(B)** Transport-transverse cross-section through the core of the LMTZ southern wall and the front of the LMTZ northern wall. Cross-strike architectural changes highlighted within the text are numbered, whilst the forelandward expression of cross-strike discontinuities are identified.

Key

- Basal Quartzite/Overturned Basal Quartzite
- Torridon Sandstones/Overturned/ Sheared Torridon Sandstone
- Lewisian Gniess/Overturned Lewisian Gniess
- Moine Supergroup
- Fucoid Beds
- Salterella Grits
- Pipe Rock
- Unconformity
- Thrust fault
- Fault

Forelandward propagation of the Moine Thrust develops at a similar level along the Loch Maree Fault (i.e., six hundred metres above sea-level); whilst within the Loch Maree Transverse Zone northern wall, the Moine Thrust steeply cuts up-section to one kilometre above sea level, similar to that within its hinterland (Figure 5.26b [1, 2]). These observations are supported by the steep nature of the Creag Ruadh lateral ramp along the Loch Maree Fault northern wall. Conversely, the Moine Thrust within the southern wall rises along-strike from six hundred metres to over one and a half kilometres within the Beinn Eighe Massif sector, accommodating the forelandward development of the Achnashellach Culmination (Figure 5.26b [3]). Forelandward development of the Moine Thrust within the southern wall identifies an undulatory surface, resulting from differential bulging within the Kinlochewe footwall imbricates (Figure 5.27a [1]). Along the Meall a' Ghiubhais Klippe, the Moine Thrust is suggested to truncate the underlying Coulin Thrust Sheet in response to differential thrust propagation within the Klippe (i.e., Sole Thrust cuts two hundred metres higher within the south-western side, comparably to the north-eastern side; Figure 5.27b [1]).

Within the Loch Maree Transverse Zone southern wall hinterland-most transverse section, the underlying Coulin Thrust mirrors that of the overriding Moine Thrust, indicating a joint development during forelandward propagation, maintaining its two hundred metre thickness along-strike and within the transport direction (Figure 5.26a [4, 5]; 5.26b [4]). The Coulin Thrust within the hinterland transverse section appears to laterally truncate the underlying Kinlochewe Thrust Sheet south-westwards across the Beinn Eighe Massif (Figure 5.26a [5]). Its forelandward propagation then mirrors that of the underlying Kinlochewe Thrust into the next forelandward transverse section (Figure 5.26b [4]).This suggests that deformation within the Kinlochewe footwall is amplified into the overlying Kinlochewe and Coulin thrust sheets (Figure 5.26b [4]). Within the transverse section located in front of the Meall a' Ghiubhais Klippe (Figure 5.27a), Coulin thicknesses are

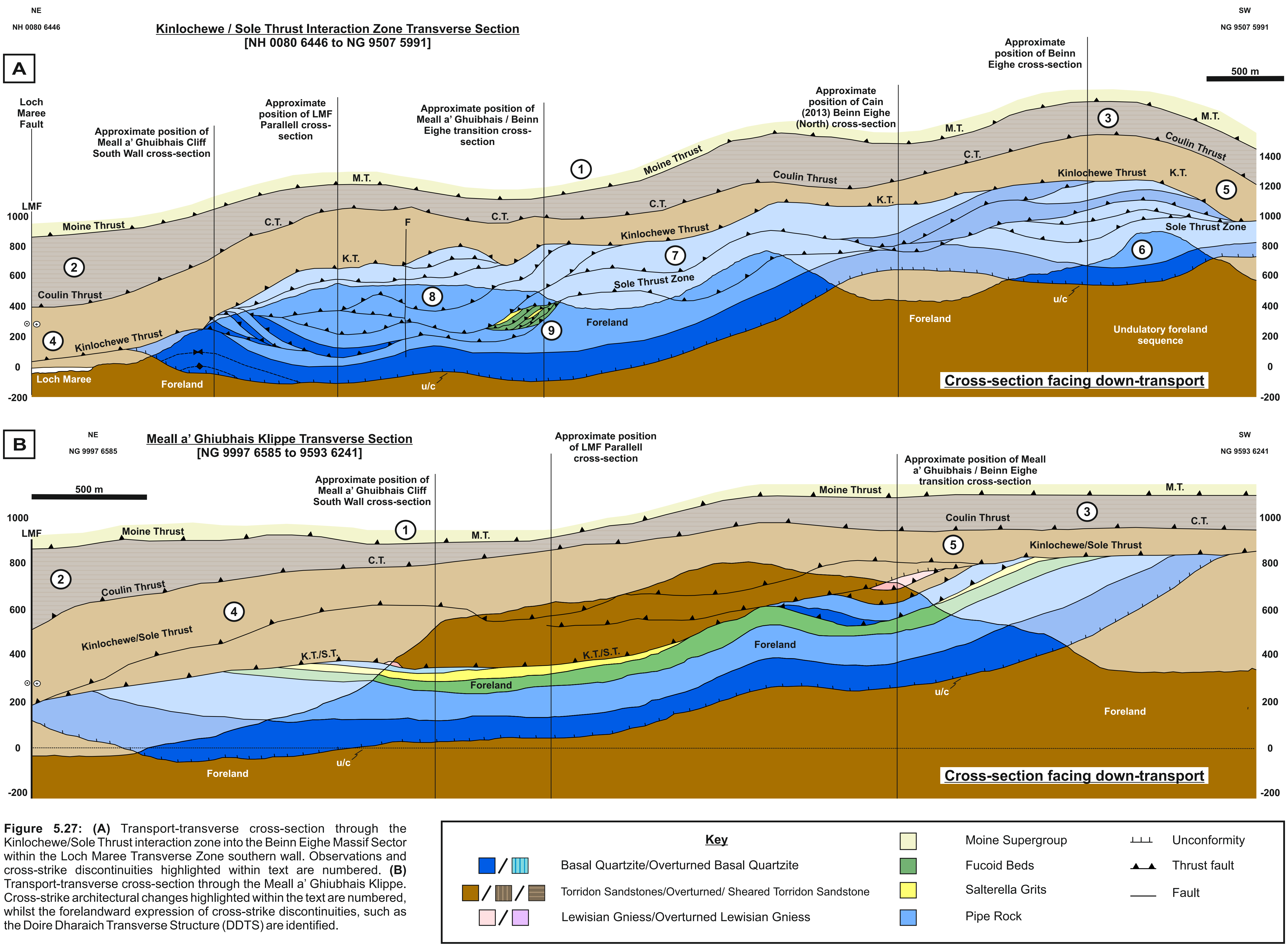


Figure 5.27: (A) Transport-transverse cross-section through the Kinlochewe/Sole Thrust interaction zone into the Beinn Eighe Massif Sector within the Loch Maree Transverse Zone southern wall. Observations and cross-strike discontinuities highlighted within text are numbered. **(B)** Transport-transverse cross-section through the Meall a' Ghuibhais Klippe. Cross-strike architectural changes highlighted within the text are numbered, whilst the forelandward expression of cross-strike discontinuities, such as the Doire Dharaich Transverse Structure (DDTS) are identified.

indicated to drastically alter along-strike as a result of interactions between the down-cutting Kinlochewe Thrust and the rising Sole Thrust Zone, and along-strike differential development of the Kinlochewe footwall imbricates. Thicknesses develop from four hundred metres along the Loch Maree Fault, to two hundred metres across the Beinn Eighe Massif (Figure 5.27a [2, 3]; 5.27b [2, 3]).

Within the Loch Maree Transverse Zone northern wall, the Coulin is displaced a minimum of one kilometre by the Loch Maree Fault before being identified within Drochaid a' Ghlinne [NH 0471 6184]. Coulin Thrust Sheet sequences drastically thicken northwards across the Loch Maree Fault from five hundred metres to one kilometre (Figure 5.25b [10]; 5.26a [4]), suggesting that the Coulin Thrust propagated further and deeper within the Loch Maree Transverse Zone northern wall, cannibalising underlying undeformed Torridonian sequences. The Coulin Thrust Sheet sequence is then not observed within the north-eastern side of the Glen Bruachaig-Incheril Window domain until north of the Ath na Sealga Fault within the footwall of the Moine Thrust. It is back-stepped by the Innis Dhriseach and Garbh Leathad transverse structures and subsequently truncated by the Moine Thrust within the northern wall, indicating a complex northern development which is not completely laterally continuous (Figure 5.25b; Table 5.2). No forelandward evidence of the Coulin Thrust Sheet is observed within the northern wall, suggesting that the Moine Thrust truncates the underlying Coulin Thrust Sheet placing Moine Supergroup on Heights of Kinlochewe Lewisian gneisses and Torridonian sandstones during forelandward-propagation (Figure 5.26a [6]; 5.26b [5]).

The Kinlochewe Thrust, which acts as the roof-thrust to its underlying footwall imbricates, highlights lateral thickness variability within map-view from 1.26 kilometres within the Meall a' Ghiubhais sector, to only one hundred twenty to one hundred eighty metres within the Beinn Eighe Massif sector (Table 5.2). Within a vertical section however, the Kinlochewe Thrust Sheet maintains an along-strike thickness of two hundred metres within hinterland transverse sections (Figure 5.26a [7]) until it reaches the Beinn Eighe Massif, where it is truncated by later movements of the structurally higher Coulin Thrust (Figure 5.26a [5]). Forelandward development of the Kinlochewe Thrust Sheet within the Loch Maree Transverse Zone southern wall is dramatically affected by the underlying nature of footwall imbricates. Along-strike however its vertical thickness is maintained forelandward into the Loch Maree Transverse Zone core (Figure 5.26b [6]), before a drastic architectural change is observed within the front of the Meall a' Ghiubhais Klippe (Figure 5.27a).

Within the Kinlochewe / Sole Thrust interaction transverse section, lateral thickness variations of undeformed Torridonian sandstones are identified within the Kinlochewe hanging-wall. Cross-strike thicknesses develop from four hundred metres at the Loch Maree Fault (Figure 5.27a [4]), to two hundred metres south-westwards towards Beinn Eighe (Figure 5.27a [5]); resulting from differential footwall imbricate bulging and out-of-sequence movements along the Coulin Thrust. Forelandward into the Meall a' Ghiubhais Klippe transverse section, a northeast-southwest architectural change is observed. North-eastwards across-strike, the Kinlochewe and Sole thrusts cut deeper into underlying foreland successions; emplacing a 'wedge' of Torridonian sandstones (i.e., the Meall a' Ghiubhais Klippe), and lowering the Sole Thrust by two hundred metres towards the Loch Maree Fault (Figure 5.27b). This two hundred metres southwest to northeast along-strike difference preserves a thicker (five hundred metre) sequence of Torridonian sandstones along the Loch Maree Fault (Figure 5.27b [4]) comparable to one hundred metre sequences south-westwards (Figure 5.27b [5]). This along-strike thickness change is suggested to occur as a result of thrust nucleations bulging the Kinlochewe Thrust Sheet off the south-western edge of the Klippe at the Kinlochewe / Sole Thrust interaction point (Figure 5.27b [5]).

Within the Loch Maree Transverse Zone northern wall, no like-for-like lateral continuity of the Kinlochewe Thrust Sheet is identified at the same structural level. The closest lateral equivalent to the Kinlochewe Thrust Sheet which is located twenty metres above the Loch Maree level within the southern wall, is the Coire Each, carrying right-way-up sequences of Torridonian sandstones and Eriboll Formation Basal Quartzites within its forelandmost expression two hundred metres above the loch level within the northern wall (Figure 5.26a [8]). However, the Coire Each, and overlying overturned sequences of the Meallan Ghobhar Thrust Sheet, is capped by right-way-up Lewisian gneisses and Torridonian sandstones of the Heights of Kinlochewe Thrust Sheet. The Kinlochewe Thrust within the southern wall carrying undeformed Torridonian sandstones and its Eriboll Formation dominant footwall imbricates are truncated against this northern wall Heights of Kinlochewe sequence, along the Creag Ruadh Lateral Ramp / Sidewall (Figure 5.26a [7, 9]).

Once dextral displacement of the Loch Maree Fault is removed, a potential cross-strike linkage is identified within field observations along the base of Torran nan Teud [NH 0473 6226] within the south-western corner of the Glen Bruachaig-Incheril Window (Figure 5.25b [11]). A small equivalent section of undeformed Torridonian sandstone, within the Heights of Kinlochewe Thrust Sheet, is identified before rapidly cutting-down stratigraphically to right-way-up Lewisian gneisses along the Innis Dhriseach Transverse Structure (IDTS) (Figure 5.25b [4]). This suggests that the Kinlochewe Thrust develops northwards across the Loch Maree Fault and rapidly cuts-down stratigraphically into basement lithologies within the northern wall. The Kinlochewe (*senso stricto*) therefore transforms into the Heights of Kinlochewe Thrust, carrying right-way-up Lewisian gneisses and Torridonian sandstone sequences within its hanging-wall. These sequences are not observed elsewhere within the Achnashellach Culmination or the Loch Maree Transverse Zone southern wall. The lateral equivalent of the Kinlochewe Thrust Sheet (i.e., Coire Each) is suggested to branch off the Creag Ruadh Lateral Ramp footwall as a separate entity (Figure 5.25b [11]), whilst the structurally higher overturned Meallan Ghobhar Thrust Sheet has a far more complex evolutionary history.

Eriboll Formation dominated footwall imbricates of the Kinlochewe Thrust Sheet, as highlighted by previous observations, indicate drastic cross-strike changes in thrust architecture, defining the Loch Maree Transverse Zone (LMTZ) southern wall, and assisting pre-thrust template reconstructions. Within the Loch Maree Transverse Zone southern wall hinterland, several major thrust imbricates carrying pre-thrust folds are identified which are laterally continuous from the Beinn Eighe Massif southern wall to interactions within the Sole Thrust along the Meall a' Ghiubhais sector cliff line (i.e., Meallan na Circe-fraoich, Coire Domhain and Sgurr na Conghair thrusts; Figure 5.26a [10]). Two décollement horizons are identified; the structurally higher incorporates the aforementioned thrusts within an eight hundred metre, Eriboll Formation dominant, structural package developing north-eastwards into a two hundred metre structural package along the Torridonian sandstone and Eriboll Formation unconformity interface, whilst the lower entrains two hundred metres of Torridonian sandstones (i.e., Achnashellach Culmination Sole Thrust). These merge northwards defining a sub-décollement pre-thrust template discontinuity (i.e., the Leathad Buidhe Transverse Structure; Figure 5.26a [11]).

Forelandward imbricates (i.e., Toll Ban and Coire an Laoigh thrusts) incorporate Torridonian sandstones and Eriboll Formation lithologies of the structurally lower Sole Thrust. The Toll Ban and Coire an Laoigh thrusts develop north-westwards towards the Loch Maree Fault from two dominant and entirely separate thrust imbricates carrying different structural packages (Figure 5.26b [7]) into a transition zone where the two thrust imbricates interact (Figure 5.26b [8]). The overriding Creag Dhubh Thrust merges with the Toll Ban Thrust northwards linking thrust imbricates developed within the higher and lower décollements along-strike (Figure 5.26b [9]). Within the Meall a' Ghiubhais sector, these thrust imbricates develop from a complex interaction (i.e., Toll Ban / Coire an Laoigh Splay System; Figure 5.26b [10]), into a dominant five hundred metre ramp identified within the Cadh' a' Mheanbh-chruidh / Carraig Alltan Mhic Eoghainn cliff line.

The Achnashellach Culmination Sole Thrust develops north-eastwards from two décollements to a single décollement identified cutting down the Cadh' a' Mheanbh-chruidh / Carraig Alltan Mhic Eoghainn cliff line within the hinterland Loch Maree Transverse Zone southern wall. Within foreland sections of the Sole Thrust Zone, diffuse imbricates develop north-eastwards into two dominant thrusts, which progress into complex interactions associated with the down-cutting Kinlochewe Thrust bulging the thrust front (Figure 5.27a [6, 7, 8]). A series of sub-décollement cross-strike discontinuities within the pre-thrust template are identified (Figure 5.26a [11]; 5.26b [11]). The Coire Each Thrust is the lateral along-strike Sole Thrust equivalent within the Loch Maree Transverse Zone northern wall (Figure 5.26a [8]). Cross-strike linkages within the Sole Thrust, Kinlochewe footwall and hanging-wall sequences, and structurally higher thrust sheets within the southern and northern wall, are controlled by the pre-thrust template which they are presented with during forelandward thrust propagation.

5.2.2. Forelandward continuity of transport-transverse structures: Pre-thrust template

Within the Loch Maree Transverse Zone southern wall hinterland, the Leathad Buidhe Transverse Structure (LBTS) is identified along the north-westward merger of two décollements forming the Achnashellach Culmination Sole Thrust (Figure 5.26a [11]). This structure defines a potential step within the pre-thrust template dropping the Sole Thrust by four hundred metres south-westwards within Torridonian sandstones (Figure 5.28 [1]). Forelandward continuity of this structure is identified within the hanging-wall of the Toll Ban Thrust as a section of entrained Torridonian sandstones (Figure 5.26b [12]; 5.28 [2]).

South-westwards, the Sole Thrust in response to the Leathad Buidhe Transverse Structure and the along-strike Beinn Eighe Lateral Ramp, cuts deeper within the Torridonian sandstone sequence resulting in a large (two hundred to four hundred metre) wedge of Torridonian sandstone material becoming entrained within the Toll Ban, Coire an Laoigh and Sole Thrust Zone imbricates (Figure 5.26b [9]; 5.28 [3]). The Sole Thrust is observed again cutting deeper into Torridonian sandstone sequences northwards along-strike indicating a frontal step which is presented to the Sole Thrust and becoming entrained within the thrust sequence (Figure 5.26b [11]; 5.28 [3]).

North-westwards along-strike within the Meall a' Ghiubhais sector, the Doire Dharaich Transverse Structure (DDTS) is identified (Figure 5.26b [13]). This structure comprises a pre-thrust fold, down-warped south-westwards over either a small step or deflection within the pre-thrust Torridonian sandstone surface. This structure is subsequently truncated by later thrust imbricates along the Torridonian sandstone and Eriboll Formation unconformity interface. It is also aligned within the transport direction with pre-thrust folds within the Meall a' Giubhas hillside, the north-westwards rise of the Sole Thrust, and

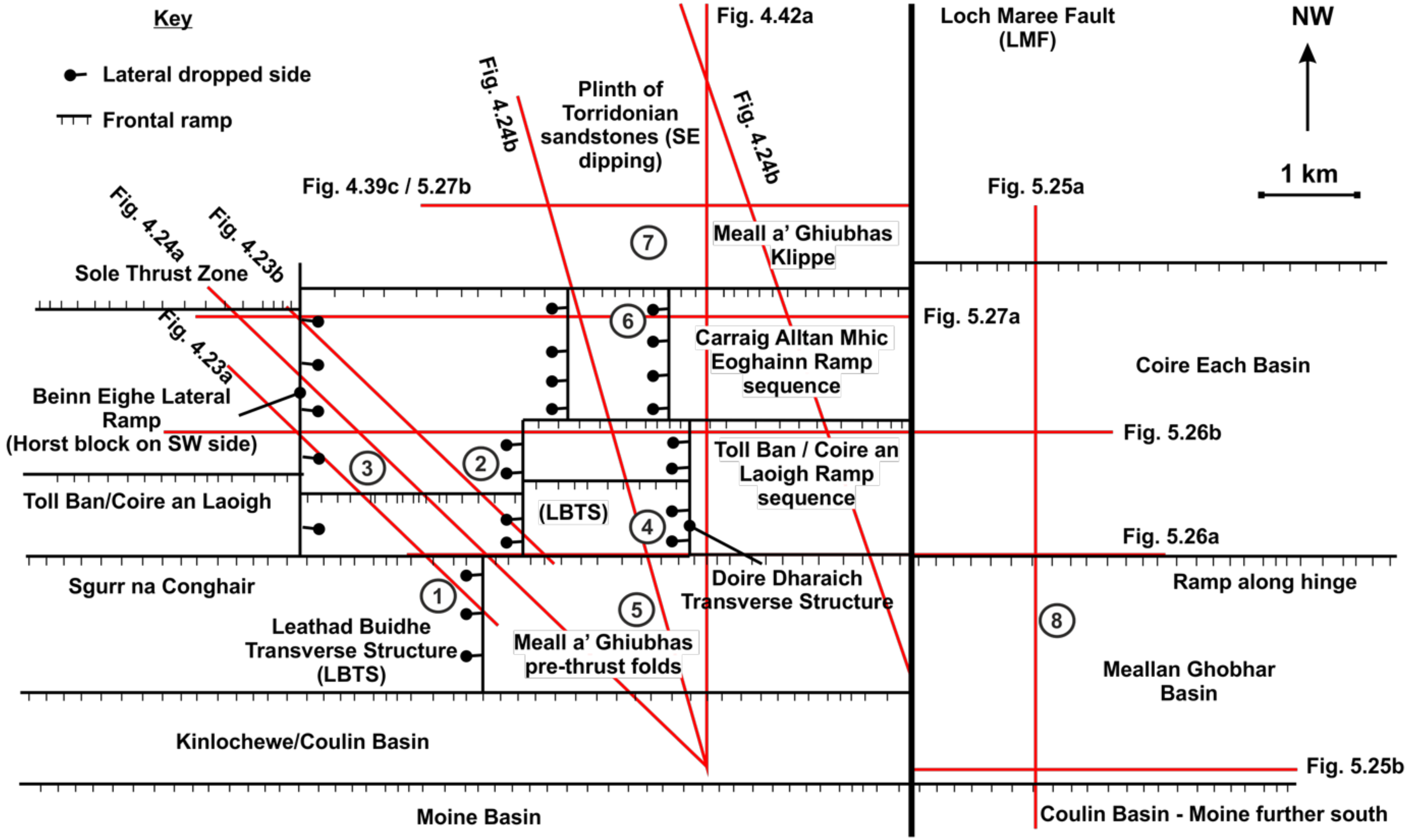


Figure 5.28: Pre-thrust template highlighting proposed frontal and lateral structures within the southern and northern walls of the Loch Maree Transverse Zone (LMTZ). Cross-strike locations of these structures developed from transport-parallel and transport-lateral cross-sections and map-view observations. Locations of transport-lateral and transport-parallel cross-sections are highlighted (red), whilst observations identified within the text are numbered. A regional-scale pre-thrust template block model is presented within the discussion to highlight the development of the LMTZ.

cross-strike structural style changes along the Toll Ban and Coire an Laoigh thrusts (Figure 5.26a [12]; 5.26b [13]; 5.28 [4, 5]). Furthermore, this forelandward discontinuity bounds the Toll Ban / Coire an Laoigh Splay System on its south-western side, resulting in a bulging of the thrust system along the Meall a' Ghiubhais sector cliff line (Figure 5.26b [10]).

Forelandward continuity of cross-strike discontinuities associated with the Doire Dharaich and / or subsequent small steps are identified within the Meall a' Ghiubhais / Sole Thrust transverse section, as a series of An t-Sron Formation imbricates developed within the Sole Thrust Zone (Figure 5.27a [9]). Preservation of these imbricates within the Sole Thrust Zone suggests a parent structure which protects these less competent lithologies and entrains them forelandward creating a two hundred metre thick imbricate sequence (Figure 5.28 [6]). Further Doire Dharaich aligned discontinuities are identified within the Meall a' Ghiubhais Klippe transverse section, as a series of Sole Thrust footwall imbricates truncating the foreland (Figure 5.27b [5]; 5.28 [7]).

A series of potential frontal and lateral linkages within the Loch Maree Transverse Zone southern wall pre-thrust template are therefore identified assisting cross-strike development. Conversely, within the Loch Maree Transverse Zone northern wall, no forelandward discontinuities are identified associated with the Innis Dhriseach Transverse Structure (IDTS), or the Garbh Leathad Transverse Structure (GLTS), indicating that they are confined to the Glen Bruachaig-Incheril Window domain. This does however have important implications for the cross-strike development of the Loch Maree Transverse Zone (LMTZ) as a whole. It therefore indicates that within the Loch Maree Transverse Zone northern wall, discontinuities are confined to the Coire Each Thrust Sheet within the footwall of the Meallan Ghobhar Thrust, which within the pre-thrust template must have once been a separate basin comprising right-way-up successions (Figure 5.28 [8]). The present location of the Glen Bruachaig-Incheril Window must therefore have once been a hinge area for overturning this basin succession.

5.3. Discussion

The Loch Maree Transverse Zone (LMTZ) which disrupts the thrust architecture within the Kinlochewe district of the Achnashellach Culmination has the following pertinent characteristics:

- Cross-strike change in structural packages observed. Develop north-eastwards from classically imbricated Torridonian-Cambrian successions which vary along strike from one and a half kilometre ‘slab-like’ thrust imbricates (i.e., Beinn Eighe Massif sector) to two hundred metre Eriboll Formation ‘flap-like’ geometries (i.e., Meall a’ Ghiubhais sector) to right-way-up and overturned slabs of Torridonian sandstones and Lewisian gneisses, overlying a right-way-up Cambrian succession (i.e., Height of Kinlochewe sector). Observations contrast markedly with those of Mathews (1984) and Butler *et al.,* (2007).

- Within the Loch Maree Transverse Zone southern wall, a northeast-southwest drastic reduction in Torridonian sandstones from one kilometre within the Beinn Eighe Massif to zero metres within the Meall a’ Ghiubhais sector is identified. Reduction accommodated by the Beinn Eighe Lateral Ramp and small along-strike steps (i.e., Leathad Buidhe / Doire Dharaich Transverse System).

- Series of northwest-southeast cross-strike changes in thrust geometry observed within the Loch Maree Transverse Zone southern wall. Thrusts coalesce northwards along several dominant thrusts from two different Torridonian sandstone dominant structural packages (i.e., Beinn Eighe Massif southern wall) into two dominant ramps identified along the Meall a' Ghiubhais sector cliff line. Thrust imbricate styles within Loch Maree Transverse Zone southern wall vary along-strike within the transport direction dependant on pre-thrust template obstacles faced during thrust propagation and cross-strike coalescing thrusts.

- Loch Maree Transverse Zone northern wall dominated by Glen Bruachaig-Incheril Window within which several transport-transverse structures are identified (i.e., Innis Dhriseach and Garbh Leathad). No forelandward continuity of structures indicates overriding thrust sheets control forelandward development. Steep lateral ramp (i.e., Creag Ruadh Lateral Ramp / Sidewall) identified within Heights of Kinlochewe Thrust Sheet confines underlying Coire Each and Meallan Ghobhar thrust sheets.

- Thrusts within the Loch Maree Transverse Zone northern and southern walls highlight numerous examples of out-of-sequence and / or oscillatory thrusting within a 'stop-start' forelandward-propagating, 290 / 300°-vergent thrust system. Transpressional structures observed within the northern and southern walls, predominantly the northern wall (i.e., 'Burn of Bones').

- Cross-strike linkages identified within the Moine and Coulin thrusts sheets between the southern and northern walls. No cross-strike equivalent for the underlying Kinlochewe Thrust Sheet, indicating that cross-strike discontinuities predominantly affect the lowest thrusts and their subsequent development. Impacts are amplified into overlying structurally higher thrust sheets.

Three-dimensional distributions of map-patterns and cross-strike linkages permit the evolution of the Loch Maree Transverse Zone to be determined. Role of the pre-thrust template and subsequent thrust translation direction upon this evolution is also ascertained.

5.3.1. Development of the Loch Maree Transverse Zone (LMTZ)

Development of the Loch Maree Transverse Zone (LMTZ) is invariably linked to the development of the Loch Maree Fault (LMF). This structure which trends west-northwest to east-southeast, aligned sub-parallel to thrust transport, is associated with a narrow Proterozoic (Laxfordian) shear zone (Park, 2002). It is this structure which focuses along-strike development of the Loch Maree Transverse Zone. Previous authors have suggested that the Loch Maree Fault links with major faults such as the Minch Fault along the Outer Isles, thereby acting as a regionally dominant structure (e.g., Coward *et al.,* 1989; British Geological Survey, 1999; Park 2002; Butler *et al.,* 2007). This research supports these interpretations, as a distinct pre-thrust architectural cross-strike discontinuity is identified.

The Loch Maree Fault initially experiences major pre-Torridon movements, slicing the outcrop of the Loch Maree Group in two, supporting observations by Park (2002). These movements are followed by deposition of Torridonian sandstones. Within the Loch Maree Transverse Zone northern wall, at least three separate basins must have formed to accommodate the right-way-up Kinlochewe / Coire Each sequence, the overturned Meallan Ghobhar and the proto-Moine Thrust basin, most likely between 630-600 Ma (i.e., Early Ediacaran; Krabbendam pers. comms, 2011; Figure 5.29a).

Conversely, within the southern wall, a single much larger basin is interpreted accommodating a much greater throw within the southern wall. Observations are supported by an east-west thickening of Torridonian sandstones along the Beinn Eighe Massif sector. Development of these basins, and the non-uniformed contact along-strike of the Torridon-Lewisian basement, result in a northwards thinning and a westwards

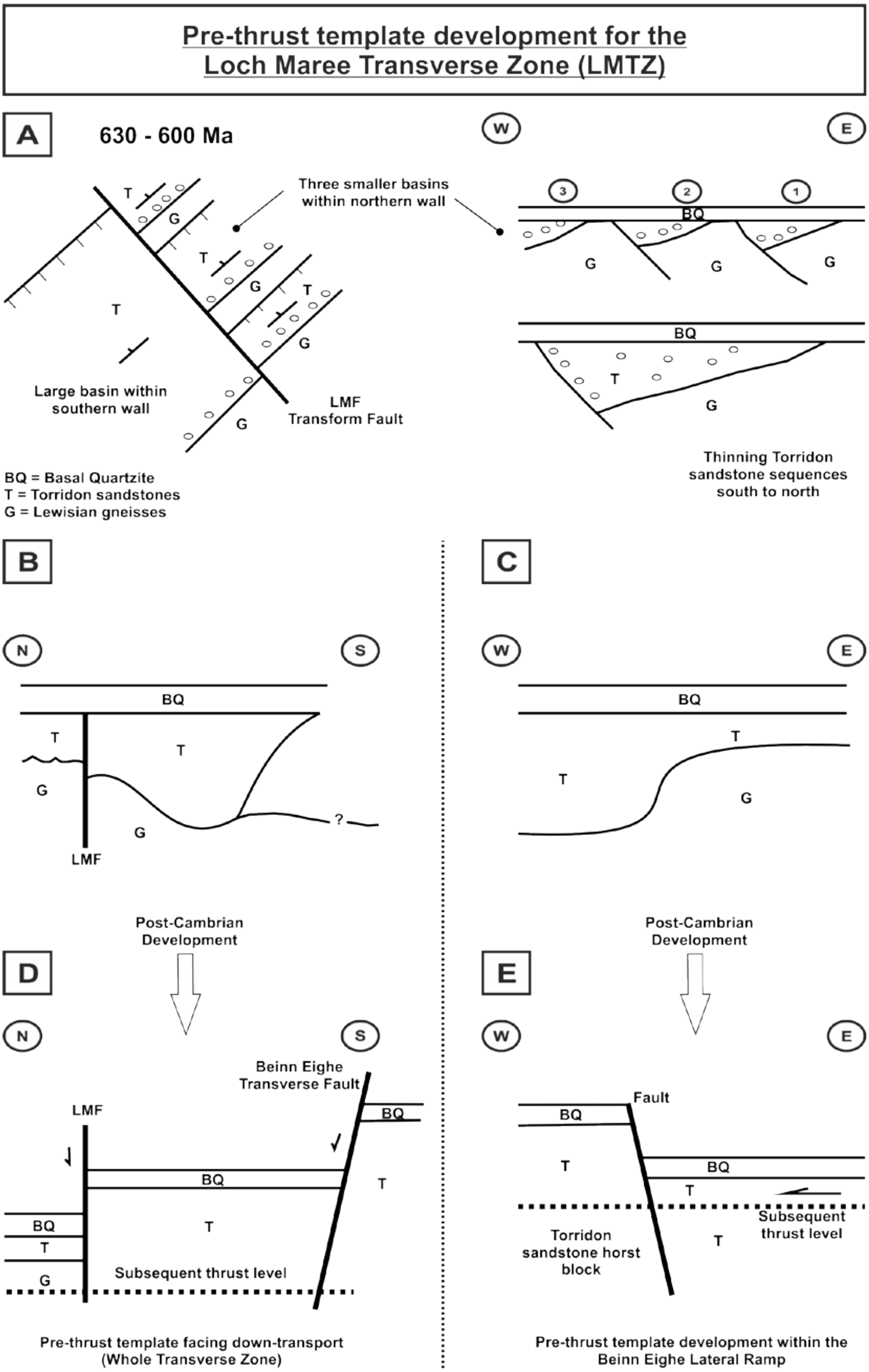


Figure 5.29: Pre-thrust template development from Torridonian deposition within the northern and southern walls **(A)**, resulting in a cross-strike (northwards) reduction in Torridon sandstones **(B)**. A forelandward thickening of Torridon sandstones is also suggested (highlighted within the Beinn Eighe Massif) **(C)**. Post-Cambrian developments incorporate fault movements along the Loch Maree Fault and the Beinn Eighe Transverse Fault, dropping the northwards side **(D)**. Movements allow Lewisian gneisses to be presented to thrusting within the LMF northern wall. Further movements are also identified within north-south orientated faults within the Beinn Eighe Massif, presenting a Torridon sandstone horst block to subsequent thrusting **(E)**.

thickening of Torridonian sandstone sequences (Figure 5.29b, 5.29c). This development does however, only affect the along-strike thickness of Torridonian sandstones as the overlying Cambrian successions are unaffected (i.e., Eriboll and An t-Sron Formations; Figure 5.29b).

This along-strike stratigraphical discontinuity is followed by post-Cambrian movements along the Loch Maree Fault, dropping the northern wall by at least one thousand five hundred metres, allowing Lewisian gneisses to be entrained within subsequent thrust translation (e.g., British Geological Survey, 1999; Park, 2002; Figure 5.29d). The Beinn Eighe lateral ramp is also dropped on its northern side, further varying along-strike and cross-strike Torridonian sandstone distributions. Cain (2013) also highlights a north-south orientated fault off the Beinn Eighe lateral ramp which drops eastwards during the Ordovician, presenting a large horst block to subsequent thrusting. This sequence is identified within the Coire an Laoigh hanging-wall within the southern side of the Beinn Eighe Massif sector (Figure 5.29e). A pre-thrust template highlighting these geometries is presented within Figure 5.30.

During the Scandian phase of the Caledonian Orogeny (c. 435-415 Ma), formation of the Moine Thrust Zone is suggested to have begun with inversion of the proto-Moine Thrust basin. Forelandward development of the Sole Thrust would then have produced the Kinlochewe and Coulin thrust sheets within the Moine footwall. Previous studies have suggested that the Kinlochewe / Kishorn Thrust Sheet is laterally continuous (e.g., Butler *et al.,* 2007). This research identifies that the Kinlochewe Thrust Sheet is truncated southwards by the structurally higher Coulin Thrust, indicating that synchronous movement along the Kinlochewe and Coulin thrusts may have occurred, with final movements indicating a hinterland-propagating phase of development along the

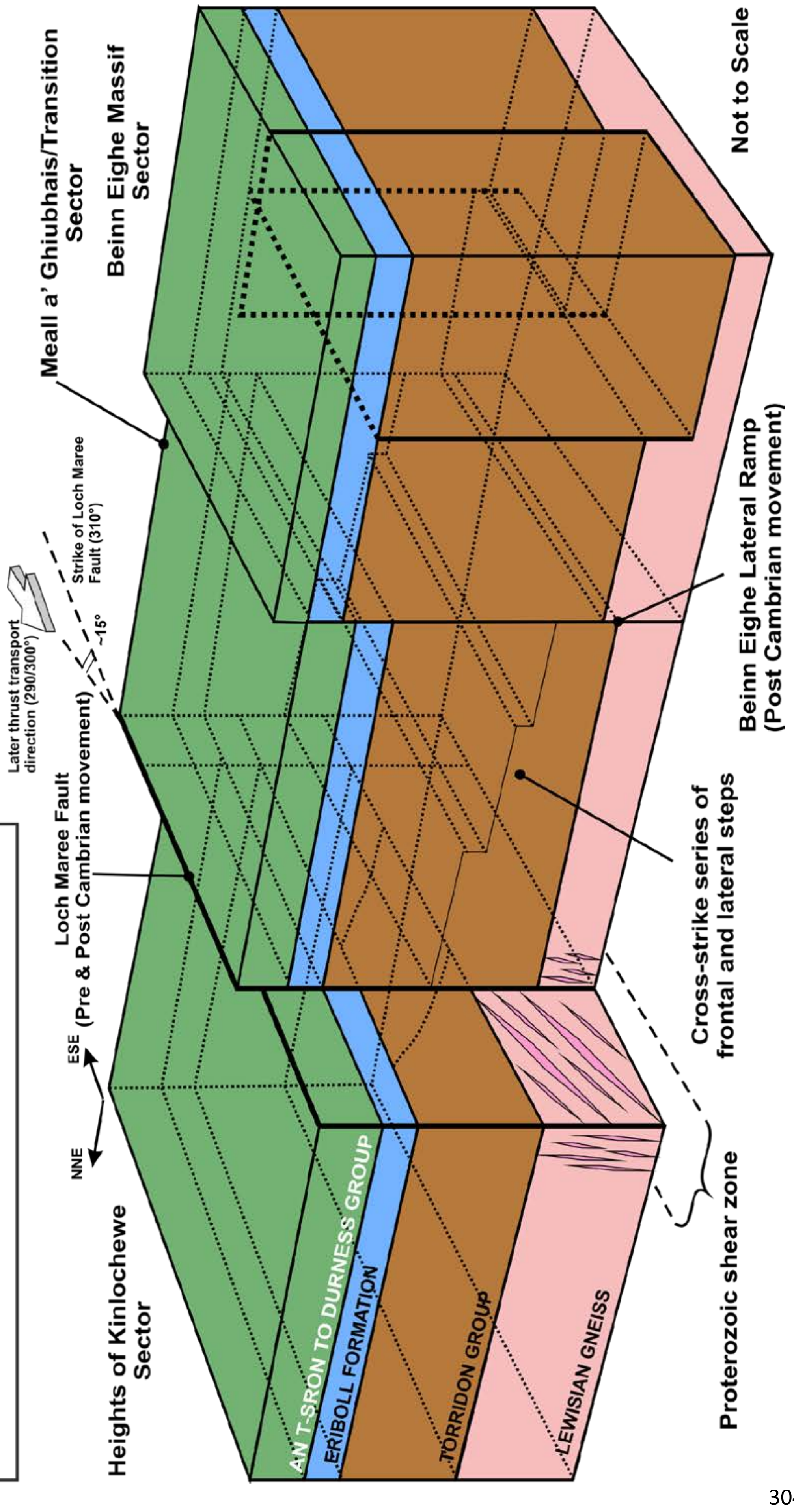


Figure 5.30: Simplified pre-thrust template of the Loch Maree Transverse Zone (LMTZ). A series of cross-strike discontinuities are identified producing along-strike variations in thrust architecture observed within modern day map-view. Major structures are highlighted within this diagram, whilst smaller cross-strike discontinuities are identified within Figure 5.28.

structurally higher Coulin Thrust. Development of the Coulin Thrust Sheet is not identified south of the Beinn Eighe Massif region at Loch Coulin, indicating that this structure separates the Kinlochewe and Kishorn thrust sheets branching northwards off the Moine Thrust footwall. It is therefore suggested that the Kinlochewe and Coulin develop within a separate basin to the along-strike Kishorn Thrust Sheet. These findings, which contradict those of Butler *et al.,* (2007), are supported by the absence of Sleat Group lithologies within the Loch Maree Transverse Zone, a sequence identified further south within the Achnashellach Culmination Kishorn Thrust Sheet. Forelandward formation of the thrust system within the footwall of the Coulin Thrust Sheet is then drastically altered within the northern and southern walls of the Loch Maree Transverse Zone.

5.3.1.1. Development of the LMTZ Southern Wall

Within the Loch Maree Transverse Zone (LMTZ) southern wall, the Kinlochewe Thrust Sheet carrying undeformed Torridonian sandstones develops; producing footwall imbricates into the thicker sedimentary pile which dominates the Achnashellach Culmination. The Kinlochewe Thrust develops forwards as the roof-thrust to this system. The Sole Thrust propagates forward within the Meall a' Ghiubhais sector along the Torridonian sandstone and Eriboll Formation unconformity interface, truncating pre-thrust folds which are produced during the development of the Coulin and Kinlochewe thrusts. No Torridonian sandstones are entrained indicating a two hundred metre 'flap-like' geometry of Eriboll and An t-Sron Formation lithologies.

Along-strike the Sole Thrust interacts with pre-thrust template features such as the Doire Dharaich and Leathad Buidhe Transverse System. As a result, the Sole Thrust develops into two décollements, one carrying just Eriboll Formation units along the unconformity interface, the second cutting deeper into Torridonian sandstones. Within the structurally higher thrust décollement, the Meallan na Circe-fraoich and Coire Domhain thrusts are formed whilst the underlying Sgurr na Conghair samples the Torridonian sandstones along-strike within the Beinn Eighe Massif sector. Within the Meall a' Ghiubhais sector these thrusts form large dominant thrusts spaced hundreds of metres apart. Transpressional shortening occurs within these structural packages as the system develops northwards over the Doire Dharaich Transverse Structure.

Forelandward propagation along the lower décollement is identified along the Toll Ban Thrust which entrains Torridonian sandstones within the thrust system. These lithologies are not present north of the Leathad Buidhe Transverse Structure. The Toll Ban Thrust subsequently approaches the Torridonian sandstone horst block identified within Cain (2013). Interactions within this structure result in oscillatory thrusting between the Toll Ban Thrust and the aforementioned thrust imbricates within the structurally higher décollement. During this phase of development the Creag Dhubh Thrust splays develop off the Toll Ban Thrust. Along-strike the Toll Ban Thrust climbs a frontal step producing the first expression of the Toll Ban / Coire an Laoigh Ramp along the Cadh' a' Mheanbh-chruidh cliff line.

The Sole Thrust within the Beinn Eighe Massif sector cuts deeper beneath the Toll Ban Thrust through the horst block, forming the Coire an Laoigh Thrust. This process would drastically slow forelandward-propagation and enhance further hinterlandward phases of movement along previously produced thrust imbricates. The Coire an Laoigh Thrust interacts along-strike with a series of steps which accommodate the northward thinning of Torridonian sandstones. These processes result in the thrust décollement climbing from Torridon sandstones into Eriboll Formation lithologies, a processes started within the hinterland over the Leathad Buidhe Transverse Structure.

The Coire an Laoigh and Toll Ban thrusts merge along strike within the Meall a' Ghiubhais sector forming the Toll Ban / Coire an Laoigh Splay system. This system highlights thin 'flap-like' imbricates within the Coire an Laoigh hanging-wall supporting development of oscillatory thrusting within the Coire an Laoigh Thrust and structurally higher Toll Ban Thrust. Oscillatory thrusting causes the Toll Ban / Coire an Laoigh Ramp to lock up, resulting in the underlying Sole Thrust propagating forward within the Carraig Alltan Mhic Eoghainn cliff line, forming the Carraig Alltan Mhic Eoghainn Ramp. This ramp carries large hanging-wall anticlines formed during out-of-sequence thrusting within the hinterland Toll Ban / Coire an Laoigh Ramp and loading from the overlying Kinlochewe roof-thrust sequence.

Propagation of the Sole Thrust within the Beinn Eighe Massif sector rises through the Beinn Eighe horst block into a level of Eriboll Formation lithologies forming a diffuse zone of thrust imbricates. Along-strike, the Sole Thrust loads underlying frontal and lateral structures within the foreland of the Sole Thrust front, resulting in the formation of a two hundred metre thick sequence of An t-Sron Formation imbricates within the Kinlochewe / Sole Thrust interaction zone. This zone is suggested to have formed as a result of the down-cutting Kinlochewe roof-thrust, entraining Eriboll Formation lithologies within its footwall, deforming the Meall a' Ghiubhais Klippe front. Structures such as the Bhanabhaig Klippe and thrust imbricates along the south-western side of the Meall a' Ghiubhais Klippe are produced as a result. This indicates that final movements along the Kinlochewe roof-thrust are out-of-sequence in response to the rise of the Sole Thrust into An t-Sron formation units within the Meall a' Ghiubhais front; an observation supported by evidence within the Ruadh Stac-Beag hillside.

5.3.1.2. Development of the LMTZ Northern Wall

In comparison to the Loch Maree Transverse Zone southern wall, the northern wall demonstrates a far more complex geological evolution. A sequence of right-way-up and completely overturned slabs of Torridonian sandstones and Lewisian gneisses, overlying a right-way-up Cambrian sequence is identified. To develop such an architectural disparity across strike two hypotheses are suggested. The first accommodates a large fold sequence which developed prior to later Scandian thrusting. This fold sequence would have been produced by one Torridonian basin being overturn over another during the early formation of the Caledonian Orogeny, producing the overturned Meallan Ghobhar Thrust Sheet over the right-way-up Cambrian sequence of the Coire Each (Figure 5.31a [1]). The basin basement Lewisian gneisses (i.e., the proto-Heights of Kinlochewe Thrust Sheet) would then overlie this sequence, followed by the Torridonian sandstone sequences which would develop into the Coulin and Moine thrust sheets (Figure 5.31a [2, 3]). Fold train would have developed a recumbent nature before the advancing thrust front truncated the sequence along the fold hinges constructing the observed map-pattern (Figure 5.31b).

Evidence to support this hypothesis is identified within the Coire Each Thrust Sheet, where large folds are truncated by the Meallan Ghobhar Thrust along major fold hinges. However, no evidence for such extensive folding is identified within the Loch Maree Transverse Zone southern wall, or within the Heights of Kinlochewe Thrust Sheet and structurally higher thrust sheets. Although such evidence may have been removed by later brittle movements of the Coulin and Moine thrusts, undeformed Scourie dyke 'swarms' within the Heights of Kinlochewe indicate little internal deformation. It is therefore suggested to be localised to the Coire Each and the overriding Meallan Ghobhar Thrust Sheet. The following hypothesis is therefore favoured for the development of the Loch

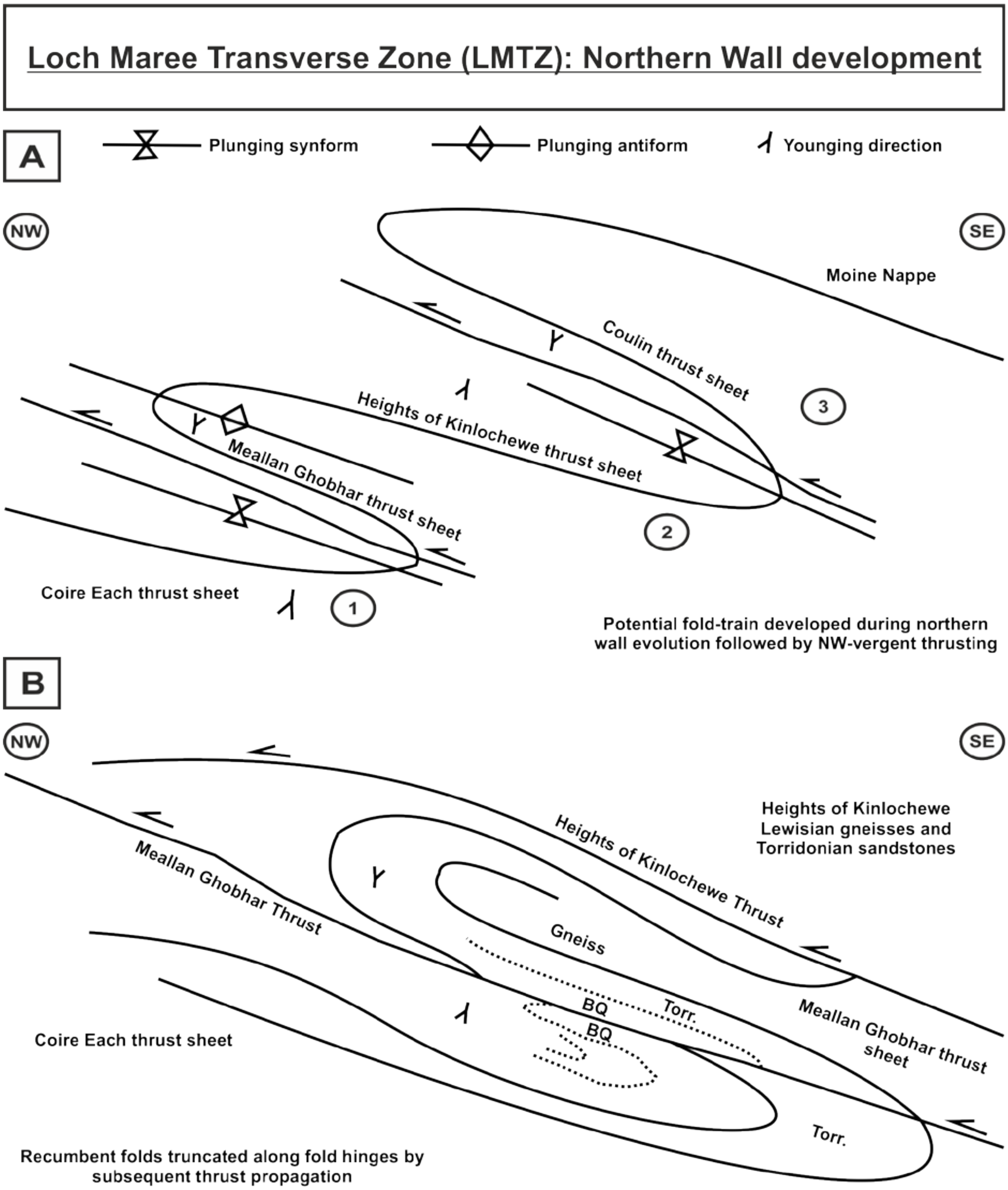


Figure 5.31: Development of the LMTZ northern wall. **(A)** One potential development for the northern wall incorporates the evolution of a fold-train in which all the lithologies comprising the different thrust sheets are placed in position before subsequent thrusting. **(B)** Second hypothesis, which is favoured here, incorporates a folded sequence incorporating the Meallan Ghobhar and Coire Each thrust sheets, above which, higher thrust sheets are loaded. This 'ice-breaker' tectonics would fracture the fold hinge resulting in the Meallan Ghobhar and Coire Each thrusts propagating forward.

Maree Transverse Zone northern wall.

Similar to the previous hypothesis, the Meallan Ghobhar Thrust Sheet would have been folded over the right-way-up Coire Each sequence forming a recumbent fold (Figure 5.31a [1]). However unlike the previous hypothesis, structurally higher thrust sheets, such as the Heights of Kinlochewe, would not have been incorporated into a fold train. Within the northern wall, the Sole Thrust (i.e., the proto-Coulin Thrust) would have cut deeper entraining and deforming Torridonian sandstones before being presented with Lewisian gneisses along the northern-dropped side of the Loch Maree Fault as a result of post-Cambrian movements (Figure 5.30). The Sole Thrust would have then propagated through the Lewisian gneisses (becoming the Heights of Kinlochewe Thrust) before meeting the pre-thrust fold comprising the Meallan Ghobhar and Coire Each thrust sheets.

The Heights of Kinlochewe Thrust Sheet would have then propagated over this fold, causing considerable footwall deformation and down-warping of the fold sequence. The Heights of Kinlochewe Thrust Sheet would also down-warp along its southern edge against the Proterozoic shear zone defining the Loch Maree Fault, forming the Creag Ruadh Lateral Ramp / Sidewall. This interpretation is supported by down-warped Lewisian gneisses highlighting horizontal Scourie dykes. Linkages with the southern wall indicate that the Kinlochewe (*senso stricto*) within the southern wall would 'root-up' under the Creag Ruadh Lateral Ramp to form the Heights of Kinlochewe Thrust, contradicting the lateral continuity suggested within Butler *et al.,* (2007) (Figure 5.32a [1]).

Within the footwall of the Heights of Kinlochewe Thrust Sheet, the Sole Thrust would be presented with the fold hinge of the Meallan Ghobhar / Coire Each fold. Loading from the

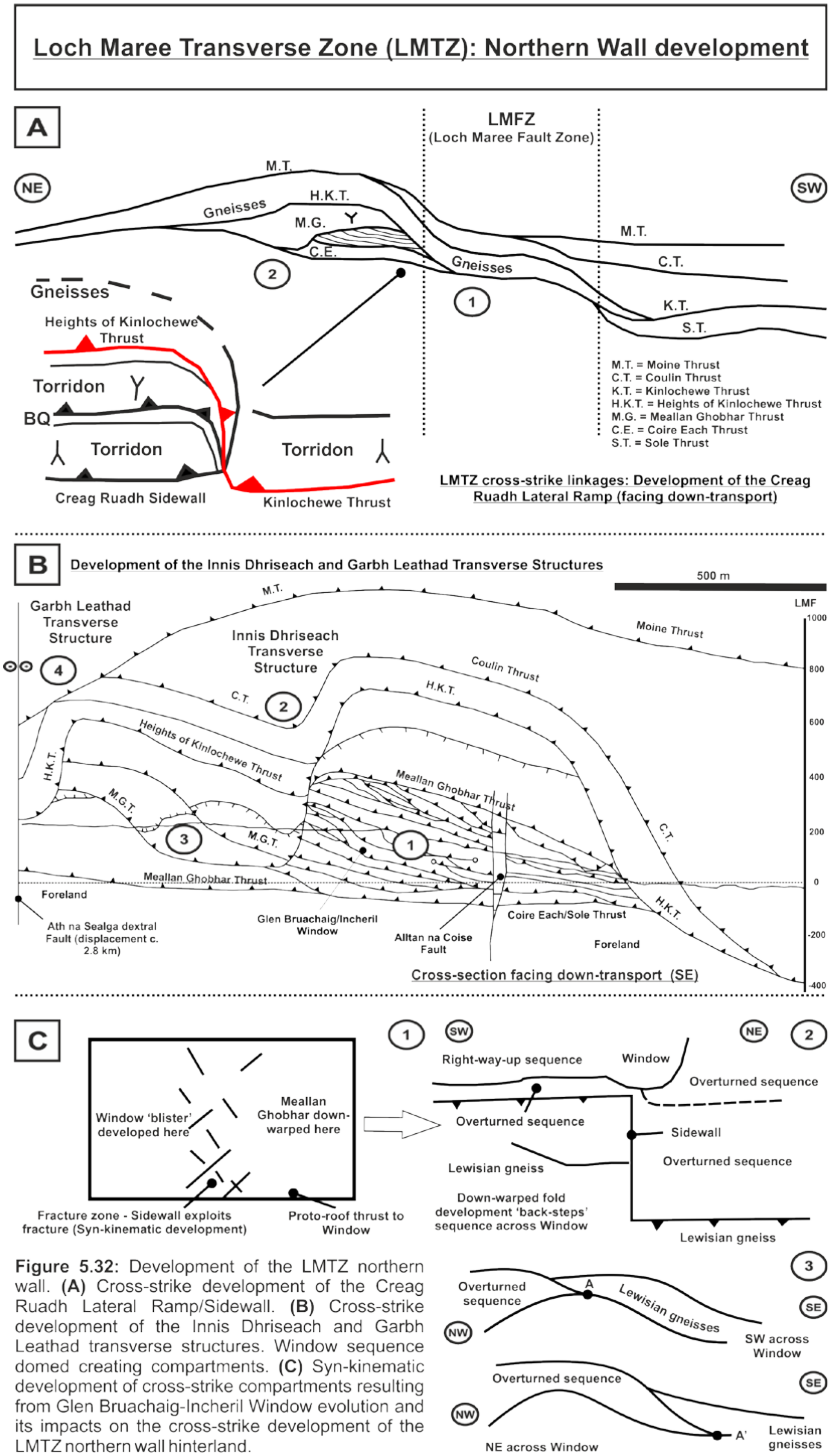


Figure 5.32: Development of the LMTZ northern wall. **(A)** Cross-strike development of the Creag Ruadh Lateral Ramp/Sidewall. **(B)** Cross-strike development of the Innis Dhriseach and Garbh Leathad transverse structures. Window sequence domed creating compartments. **(C)** Syn-kinematic development of cross-strike compartments resulting from Glen Bruachaig-Incheril Window evolution and its impacts on the cross-strike development of the LMTZ northern wall hinterland.

overlying Heights of Kinlochewe Thrust would fracture this hinge joint, acting like an "ice-breaker" allowing the Sole Thrust to penetrate. Upon reaching An t-Sron Formation lithologies, rapid production of thrust imbricates are developed beneath the proto-roof thrust sheet (i.e., the Meallan Ghobhar) (Figure 5.32a [2]; 5.32b [1]). Development of the Glen Bruachaig-Incheril Window imbricates begins nearest the Loch Maree Fault and propagates north-eastwards inflating the proto-roof thrust (i.e., the Meallan Ghobhar Thrust Sheet) like a blister, either producing a fracture, or extenuating a pre-existing fracture developed during the Height of Kinlochewe Thrust Sheet propagation (Figure 5.32c [1]). Inflation of the Window deforms this overlying proto-roof thrust sequence, producing a north-eastwards down-warped sequence (Figure 5.32b [2]). This structure develops into the Innis Dhriseach Transverse Structure (IDTS) along which the development of the Meallan Ghobhar produces thrust imbricates of folded material highlighted within map-view which are back-stepped over the Innis Dhriseach Transverse Structure (Figure 5.32b [3]; 5.32c [2, 3]).

Development of these along-strike imbricates inflates a second compartment, which is truncated by the structurally higher Heights of Kinlochewe Thrust Sheet, producing the Garbh Leathad Transverse Structure (Figure 5.32b [4]). This structure subsequently acts as a zone of weakness for the later development of brittle faults (i.e., the Ath na Sealga Fault). Development of these syn-kinematic cross-strike discontinuity structures further bulges the hinterland zone of the northern wall, resulting in increased forward loading and potentially causing oscillatory thrusting between the Heights of Kinlochewe Thrust and structurally lower thrusts.

Once the hinge zone is truncated and forelandward-propagation is restored along the Coire Each and Meallan Ghobhar thrusts, the overriding Meallan Ghobhar Thrust Sheet cuts down-wards creating transpressional structures identified within the 'Burn of Bones' domain due to loading by the overlying Heights of Kinlochewe Thrust Sheet and lateral confinement against the Creag Ruadh lateral ramp. This internal confinement may also explain the steep synchronous forelandward climb of the Coire Each and Meallan Ghobhar thrusts into the Meallan Ghobhar hillside to try and remove these confinements.

Within this hillside, the Coire Each / Sole Thrust is identified two hundred metres above the loch level within the northern wall in comparison to the Loch Maree Transverse Zone southern wall which is only twenty metres above the loch level. Final movements identified within the Meallan Ghobhar cliff line indicate a hinterlandward-propagating phase in which the Heights of Kinlochewe Thrust truncates the Meallan Ghobhar Thrust, which truncates the underlying Coire Each Thrust. This phase may be synchronous with the final out-of-sequence movements along the Kinlochewe / Sole Thrust within the southern wall (i.e., within the Meall a' Ghiubhais Klippe front).

A comparable structure to that observed within the Loch Maree Transverse Zone northern wall is identified within the southern Moine Thrust Belt east of the Lochalsh Syncline on the Lochalsh peninsula, where at least six separate thrust sheets can be identified. These six thrust sheets alternate right-way-up and overturned successions and structurally higher thrusts truncate the underlying thrust sheet, demonstrating a hinterland-propagating thrust sequence. Overturned successions show penetrative non-coaxial deformation, similar to the Meallan Ghobhar Thrust Sheet; whereas thrust sheets carrying right-way-up successions show far less internal deformation. A final phase of brittle movement is also then observed along the Moine Thrust truncating structurally lower thrust sheets and the axial trace of the Lochalsh Syncline on Skye (Leslie *et al.,* 2011).

Last phases of deformation within the Loch Maree Transverse Zone include the bulging of the southern wall during development of the Achnashellach Culmination, indicating a final foreland-propagating phase of movement. This is followed by brittle processes including, sinistral and dextral movements along the Loch Maree Fault displacing all observed thrust sheets, and the formation of large dextral faults (e.g., Ath na Sealga Fault) which displace all sequences up to and including the Moine Thrust. This structure is suggested to be a Rheidol shear developed 60° from the Loch Maree Fault, and linked to its development. Development of the Loch Maree Transverse Zone is therefore far more complex than previously suggested by Matthews (1984) and Butler *et al.,* (2006; 2007), especially within the Loch Maree Transverse Zone northern wall.

5.3.2. LMTZ Development: Role of the Pre-thrust template

The pre-thrust template within the Loch Maree Transverse Zone has a major impact on the production of cross-strike discontinuities and cross-strike linkages within the developing Moine Thrust Belt. Discontinuities produced during pre-thrust template development determine what structures are presented to the propagating thrust front and in turn, determine what syn-kinematic discontinuities are produced. Severity of pre-thrust template discontinuities will also impact on the amplification of such features into higher thrust sheets as the thrust belt develops further.

Within the Loch Maree Transverse Zone southern wall, post-Cambrian fault movements along the Beinn Eighe Lateral Ramp cause a drastic north-eastwards reduction in the amount of available Torridonian sandstones presented to the thrust front. Ordovician fault movements within the Beinn Eighe Massif drop Torridonian sandstones resulting in horst block production, further amplifying along-strike and cross-strike architectural variations.

Structures within the pre-thrust template, such as the Leathad Buidhe and Doire Dharaich transverse structures, compartmentalise forelandward deformation, encouraging a north-eastwards rise of the Sole Thrust. These structures also produce pre-thrust folds as lithologies interact with pre-thrust irregularities and the advancing thrust front. Forelandward development of these transverse structures interact with frontal structures, loading and deforming them, resulting in further forelandward entrainment or translation of lithologies displaying differing rheological behaviours into more forelandward positions. This further enhances cross-strike disparities.

Within the Loch Maree Transverse Zone northern wall, pre-Cambrian movements along the Loch Maree Fault cause a dramatic drop in the relative thrust translation depth along-strike; whilst the presence of large pre-thrust folds greatly affect resultant structures. Development of lateral ramps are prevalent within the northern wall (i.e., Creag Ruadh, Innis Dhriseach and Garbh Leathad), whilst pre-thrust template fold structures are either incorporated or truncated by the advancing thrust front. Large pre-thrust folds emplace comparably incompetent lithologies together, producing individual compartments along-strike as lithologies interact with the propagating thrust front. Interactions produce syn-kinematic cross-strike discontinuities, further complicating the cross-strike map-view expression. Later strike-slip movements along the Loch Maree Fault and structures such as the Ath na Sealga Fault further enhance these cross-strike complications.

It is therefore evident that the pre-thrust template plays a critical role in the evolution of the advancing thrust front architectural development and subsequent syn-kinematic development of structures. Cross-strike amplification of pre-thrust template structures, and resulting discontinuities, decreases with higher advancing thrust sheets indicating the impact of the pre-thrust template decreases with time. Pre-thrust template observations within this research drastically differ to those within Butler *et al.,* (2007) in which lateral continuity was suggested for the Kinlochewe / Kishorn Thrust from the southern into the northern wall. This research has demonstrated that this is not the case. Therefore, a new pre-thrust template (Figure 5.30), and a comparable cross-strike development of the Kinlochewe / Sole Thrust from Butler *et al.,* (2007) to findings within this research is presented (Figure 5.33). Furthermore, this research shows that relatively small disturbances within the pre-thrusting template can lead to significant lateral variations in thrust geometry, especially along long-lived structures such as the Loch Maree Fault, and its related Proterozoic shear zone. This is comparable to other identified transverse zones within the Moine Thrust Belt (e.g., Oykel Bridge and Traligill transverse zones; Krabbendam & Leslie, 2010; Leslie *et al.,* 2010).

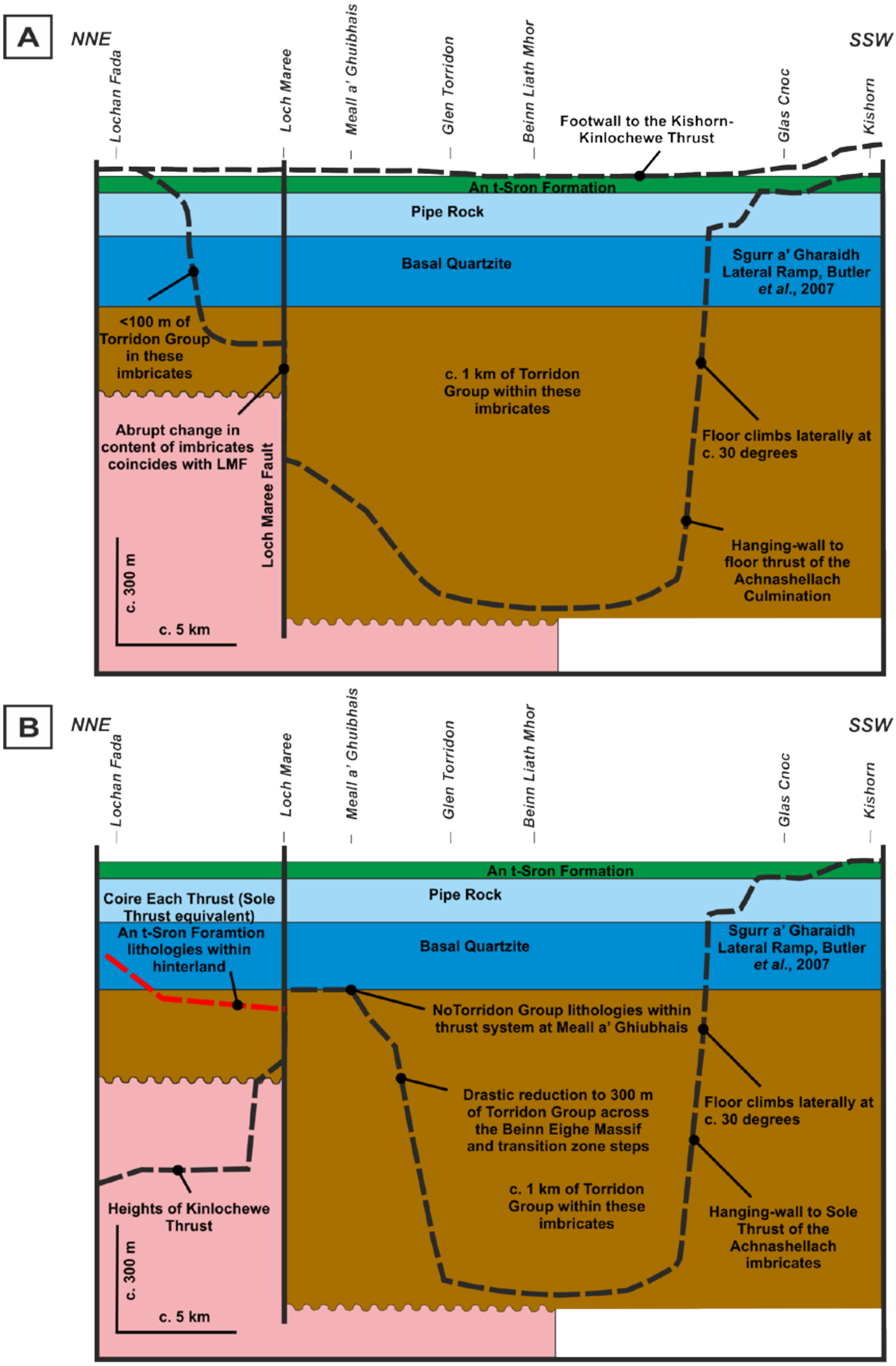


Figure 5.33: (A) Original stratigraphical separation diagram from Butler *et al.*, (2007) for imbricate thrusts within the Achnashellach Culmination, showing lateral variation in the content of imbricate slices within the Kinlochewe Thrust footwall. **(B)** New stratigraphical separation diagram highlights cross-strike imbricate thrusts within the Kinlochewe Thrust footwall. Within the northern wall, the Heights of Kinlochewe Thrust replaces the Kinlochewe Thrust (*senso stricto*), whilst the Sole Thrust equivalent is represented by the Coire Each Thrust.

5.3.3. LMTZ Development: Role of thrust transport direction

The significance of thrust transport direction on the formation of cross-strike discontinuities is highly dependent upon structures identified within the pre-thrust template and the development of syn-kinematic structures during thrust translation. In comparison to other thrust belts, such as the Cantabrian Thrust Belt, thrust translation directions are uniform along the length of the Moine Thrust Belt. As such, localised cross-strike discontinues are transported along their parent structure. Localised obliquities would still be translated along their parent structures but at oblique angles to their parent structure.

Within the Loch Maree Transverse Zone northern and southern walls, transpressional structures are identified linked to along-strike responses to the regional (290 / 300°) transport direction and the pre-thrust template. Lateral shortening of thick imbricate slices within the southern wall are observed along interaction points with pre-thrust template structures, most notable along the Leathad Buidhe and Doire Dharaich Transverse System within the Meall a' Ghuibhas hillside. Drastic architectural differences are not observed within the Loch Maree Transverse Zone southern wall due to sub-décollement structures being aligned sub-parallel to the regional (290 / 300°) transport direction. Minor thrust translation deflections are however noted across thrusts within the Beinn Eighe Massif as a result of cross-strike interactions between thick and much thinner Torridonian sandstone sequences across the Beinn Eighe Lateral Ramp. Relationships between transport sub-parallel pre-thrust template structures and regional transport have also allowed less competent lithologies to be preserved forelandward (e.g., An t-Sron Formation imbricates within the Meall a' Ghiubhais Klippe / Sole Thrust interaction zone.)

Within the Loch Maree Transverse Zone northern wall however, a far more evident transpressional overprint is identified. Thrust translation within the northern wall is slightly oblique (10 to 20°) to the strike of the Loch Maree Fault (LMF) at 310°. This cross-strike difference in alignment of pre-thrust template structures would have assisted the production of cross-strike discontinuities, such as the Creag Ruadh Lateral Ramp / Sidewall against the Proterozoic shear zone located beneath the Loch Maree Fault, and the formation of the Glen Bruachaig-Incheril Window beneath the Heights of Kinlochewe Thrust Sheet. Obliquity would have also assisted bulging of the northern wall thrust systems, causing along-strike down-cutting of the Meallan Ghobhar into the Coire Each and enhance the prospect of forelandward, transport-sub-parallel, out-of-sequence thrusting.

5.4. Summary

Within the Kinlochewe district where the Loch Maree Fault (LMF) transects the Moine Thrust Belt, a pronounced lateral change in thrust architecture is identified defining the Loch Maree Transverse Zone (LMTZ). Within the Loch Maree Transverse Zone northern wall a thrust dominated region of right-way-up and completely overturned slabs of Torridonian sandstones and Lewisian gneisses, overlying a right-way-up Cambrian succession is clearly identified. This architecture is in sharp contrast to classically imbricated repetitions of Torridonian-Cambrian rocks within the southern wall of the Loch Maree Fault. This section identifies a two hundred metre ‘thin flap’ of Eriboll Formation quartzites to the southeast of the Meall a’ Ghiubhais Klippe developing south-westwards into much thicker one and a half kilometre ‘slab-like ’Torridonian sandstone and Eriboll Formation imbricate slices that can be traced farther south within the Achnashellach Culmination. Oscillatory and out-of-sequence phases of thrusting are observed within both the northern and southern walls.

A distinct compartmentalisation of the Moine Thrust Belt architecture is therefore apparent across the Loch Maree Fault. Compartmentalisation is suggested to be a response to a significant offset of the pre-thrust template that generated a transport-parallel lateral ramp or sidewall during thrust translation (i.e., Creag Ruadh Lateral Ramp), aligned sub-parallel to a Proterozoic shear zone. Further transport-transverse structures highlighting pre-, syn- and post-thrusting cross-strike discontinues are identified within the northern and southern walls using new thrust ramp architectural analyses and transport-lateral and transport-parallel cross-sections (i.e., the Leathad Buidhe, Doire Dharaich, Innis Dharaich and Garbh Leathad transverse structures; Figure 5.34). A new pre-thrust template highlighting these structures is presented.

The Loch Maree Transverse Zone (LMTZ) therefore marks the southward change from a thrust-dominant northern Moine Thrust Belt, to the fold-and-thrust architecture identified within the southern Moine Thrust Belt, which is bulged by the still younger Achnashellach Culmination. This demonstrates a return to foreland-propagating thrusting in the later stages of development of the Moine Thrust Belt south of the Loch Maree Transverse Zone. The (brittle) Moine Thrust then truncated all of the structural elements beneath, indicating a final hinterland-propagating episode of movement all along the Moine Thrust Belt suggesting that the influence of the Loch Maree Transverse Zone, and comparable transverse zones within the Moine Thrust Belt diminished in time as the thrust belt evolved. This research shows that relatively small disturbances within the pre-thrusting template can lead to significant lateral variations in thrust geometry, especially along long-lived structures such as the Loch Maree Fault, and its related Proterozoic shear zone.

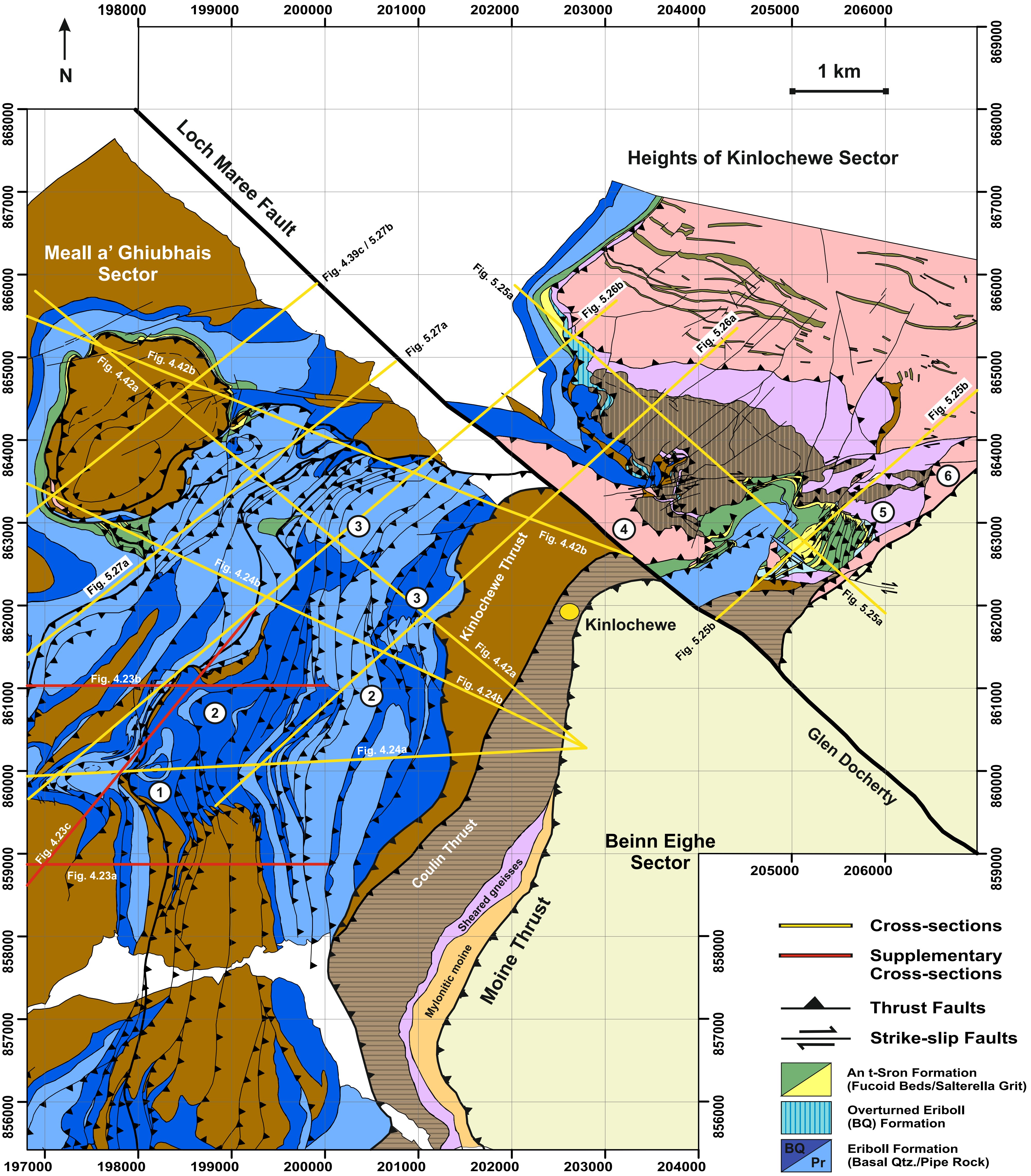


Figure 5.34: New geological map of the Loch Maree Transverse Zone (LMTZ) from detailed (2009-2012) 1:10,000-scale mapping. LMTZ laterally confined to the region between Beinn Eighe (LMTZ southern wall) and Heights of Kinlochewe (LMTZ northern wall). New transport-parallel and transport-lateral cross-section locations are identified within the new map. Newly identified transport-transverse pre-thrust and syn-kinematic cross-strike discontinuities within this research are numbered.

1 Beinn Eighe Lateral Ramp 2 Leathad Buidhe TS 3 Doire Dharaich TS 4 Creag Ruadh Sidewall

5 Innis Dhriseach TS 6 Garbh Leathad TS

Chapter Six:

Identification of potential Transverse Zones in Thrust Belts: Somiedo-Correcillas Unit, Cantabrian Thrust Belt, northern Spain

Chapter six serves to illustrate the findings of an investigatory study undertaken as part of a regional analysis identifying potential cross-strike discontinuities / transverse zones within the Somiedo-Correcillas Unit, Cantabrian Thrust Belt, northern Spain. Emphasis is placed on the application of new methodologies for the identification of transport-transverse structures and cross-strike linkages within potential transverse zones. The potential development of identified cross-strike discontinuities / transverse zones and the role of the pre-thrust template and transport direction are discussed within the wider context of the Cantabrian Thrust Belt.

6.1. Introduction

New (2009-2011) regional-scale analyses of the Somiedo-Correcillas Unit within the Cantabrian Thrust Belt (i.e., Cantabria-Asturian Arc) were undertaken using new fault network and thrust ramp analyses to identify potential cross-strike discontinuities / transverse zones. Three distinct domains highlighting different structural styles (i.e., a northern, southern and transition hinge domain) are identified, within which a series of potential cross-strike discontinuities / transverse zones are observed.

This chapter describes the geological setting and reviews pertinent research undertaken within the Cantabrian Thrust Belt and Somiedo-Correcillas Unit. Detailed analyses of the Cantabria-Asturian Arc fault network within this research are described and subsequently validated through ground-truthing and selected re-mapping during focused research.

Stratigraphical separation diagrams are implemented to identify potential transport-transverse structures, whilst transport-parallel and transport-lateral cross-sections are constructed to determine the chronology of deformation and the evolution of key structures, such as the Genestosa Fault and Cueto Negra-Brañillín Window. Observations are supported by geometrical and kinematic data collections. All localities are reprojected into a single UTM 29N projection.

The development of identified potential cross-strike discontinuities / transverse zones are discussed and placed within the wider context of the development of the Cantabria-Asturian Arc, whilst the role of the pre-thrust template and transport direction are determined. Results show the key interplay of extension, inversion, thrusting and wrench tectonics and the key role that these play in the evolution of potential cross-strike discontinuities / transverse zones and the Cantabria-Asturian Arc.

6.2. Geological Setting

The late Palaeozoic Variscan Belt of Western Europe is a broad, sinuous continent-scale oroclinal bend, extending almost four thousand kilometres and in some areas more than nine hundred kilometres, from the Betic Cordilleran, southern Spain, to the Carpathian Mountains (Weil *et al*., 2001; Veselovský, 2004; Figure 6.1). The Variscan Belt developed during the Late Devonian (380-360 Ma) in response to closure of the Rheic Ocean, and records the resulting convergence and collision of Gondwana with Laurussia, forming the Pangea supercontinent (Franke, 1992; Fernández-Suárez *et al*., 2000; Weil *et al*., 2001; 2010). Laurussia included the previously amalgamated continents of Baltica and Laurentia, and several allochthonous terranes including Avalonia (Johnston *et al*., 2013).

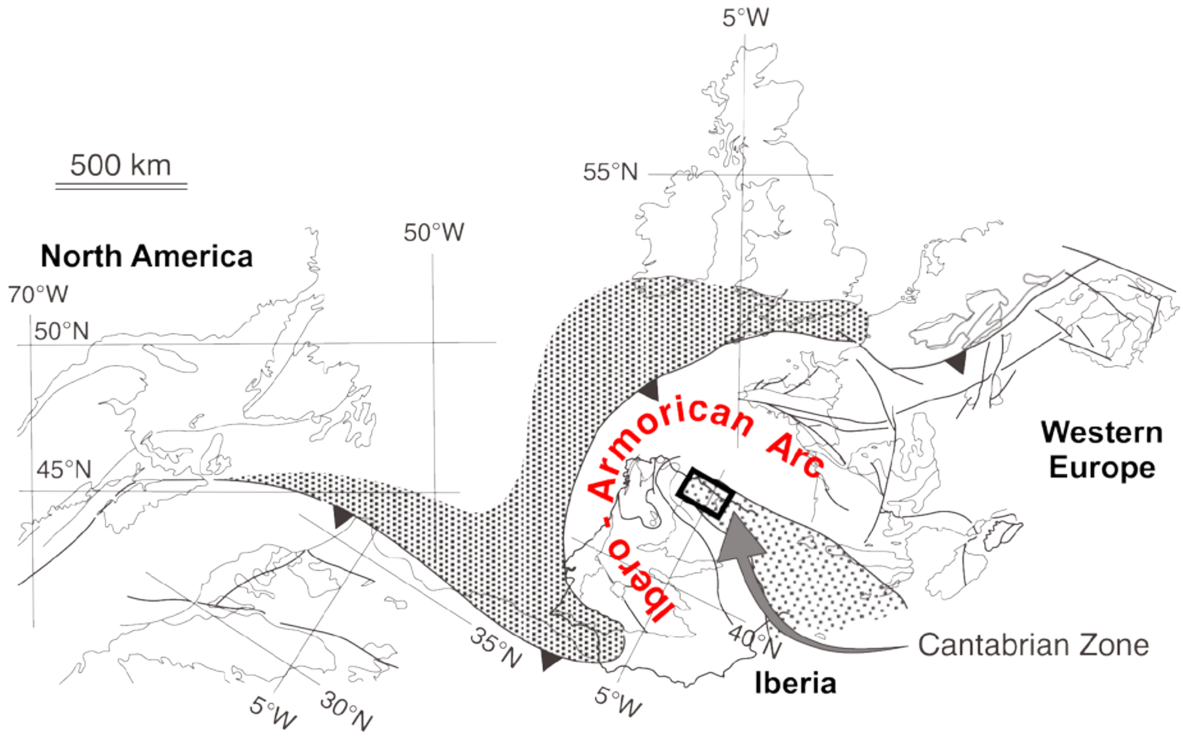


Figure 6.1: Location of the Ibero-Armorican Arc within the Variscan Orogeny in Western Europe and North America (reconstruction of Pangea in the area surrounding Iberia after Lefort, 1989). Location of Cantabria identified. Closed triangles: Variscan Front; heavy dotted: accretionary prism; light dotted: foreland fold-thrust belt (Adapted after Alonso *et al*., 2009).

The timing of orogenic development is constrained by deformation and metamorphism of Devonian and Carboniferous strata, and by Carboniferous foreland basin development (Paris & Robardet, 1990; Martínez-Catalán *et al*., 2007). Syn-kinematic remagnetisation indicates that deformation was ongoing into the Late Carboniferous and was complete prior to 310 Ma (Parés *et al*., 1994; Van der Voo *et al*., 1997; Weil *et al*., 2000; 2001; 2010; Weil, 2006).

Within the south-western Variscides, a prominent bend called the Ibero-Armorican or Cantabria-Asturian Arc is identified demonstrating nearly 180° curvature within the Iberian Massif (Figure 6.1; 6.2a; Matte, 1991; Bastida & Aller, 1992; Pérez-Estaún *et al*., 1994, Ábalos *et al*., 2002; Veselovský, 2004). The Ibero-Armorican Arc has been recently suggested to be a thick-skinned lithospheric-scale orocline that triggered lithospheric

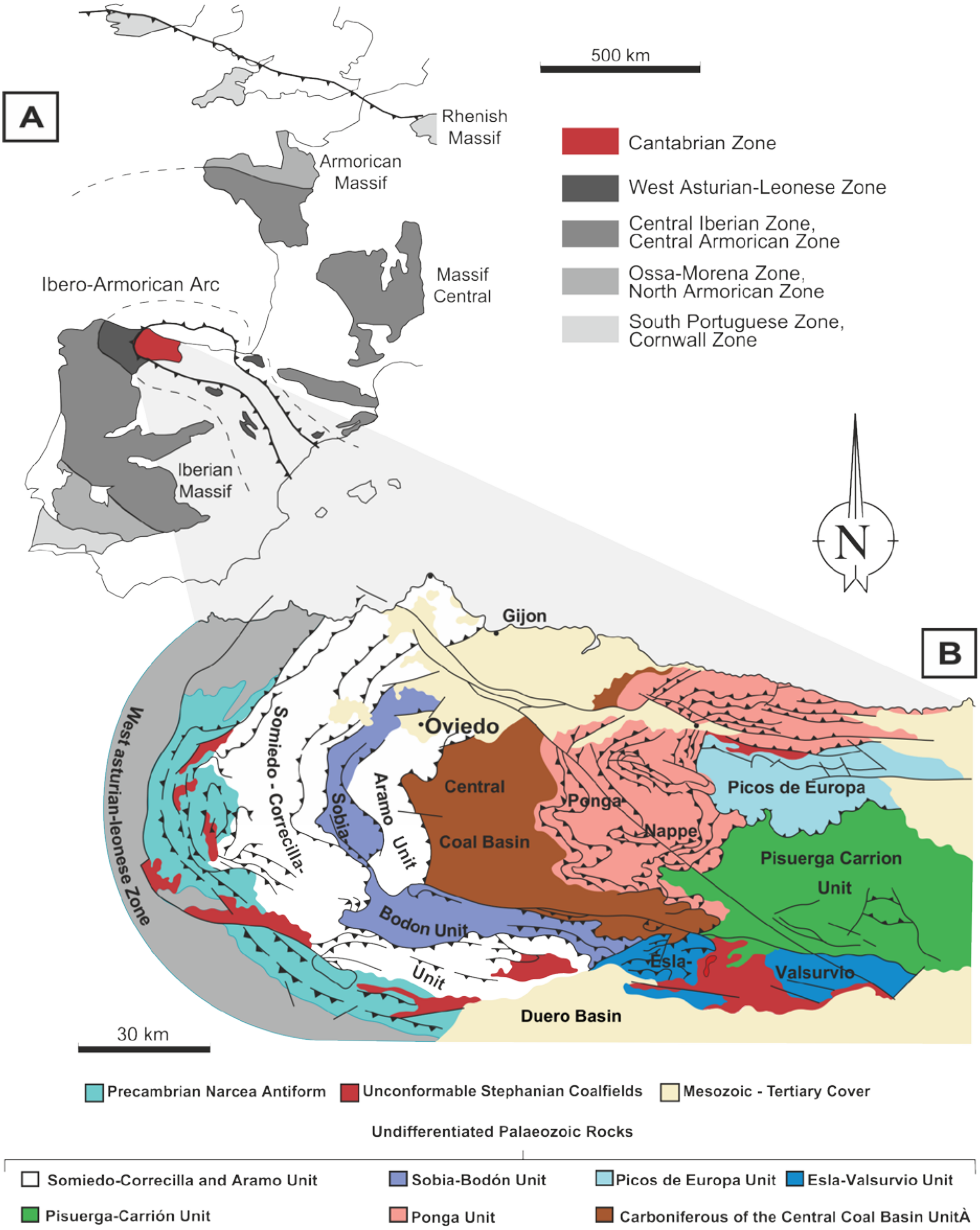


Figure 6.2: **(A)** Tectonic zonation of the Iberian Massif with correlating units within the Western Europe Variscides. (Adapted after Dallmeyer *et al.*, 1997). **(B)** Subdivision of the Cantabrian Zone highlighting its tectonic units (Adapted after Julivert, 1971 and Pérez-Estaún *et al.*, 1988).

delamination and mantle replacement (Gutiérrez-Alonso *et al*., 2004; 2011a; 2011b; Ducea, 2011). Furthermore, the Ibero-Armorican Arc has been suggested to be one of a pair of linked oroclines within Iberia, the Central Iberian Orocline being the other (Martínez-Catalán, 2011; Shaw *et al*., 2012). The Iberian part of the Variscan belt is an example of an orogenic belt lacking exposures of cratonic igneous or metamorphic basement (Fernández-Suárez *et al*., 2000; Veselovský, 2004).

The Iberian Massif is subdivided into five zones based on metamorphic, structural and palaeogeographical differences reflecting varying deformation styles (Lotze, 1945; Julivert *et al*., 1972). From northeast to southwest these include; the Cantabrian, West Asturian-Leonese, Central Iberian (including the Galicia Trás-os-Montes Zone), Ossa Morena and South Portuguese Zones (Lotze, 1945; Julivert *et al*., 1972; Figure 6.2a). Dallmeyer *et al*., (1997) provides a concise overview and absolute age information of the geotectonic evolution for the Iberian zones. The Cantabrian Zone (i.e., Cantabrian Thrust Belt) resides within the core of the Cantabria-Asturian Arc, characterised by thin-skinned tectonics with a transport-direction indicating foreland-directed concavity with inward-facing structures (De Sitter, 1962; Julivert, 1971; Pérez-Estaún *et al*., 1988; Hirt *et al*., 1992; Veselovský, 2004; Alonso *et al*., 2009). The Cantabrian Zone is further subdivided into several tectonics units (Figure 6.2b) including the Somiedo-Correcillas unit, where this research is specifically focused.

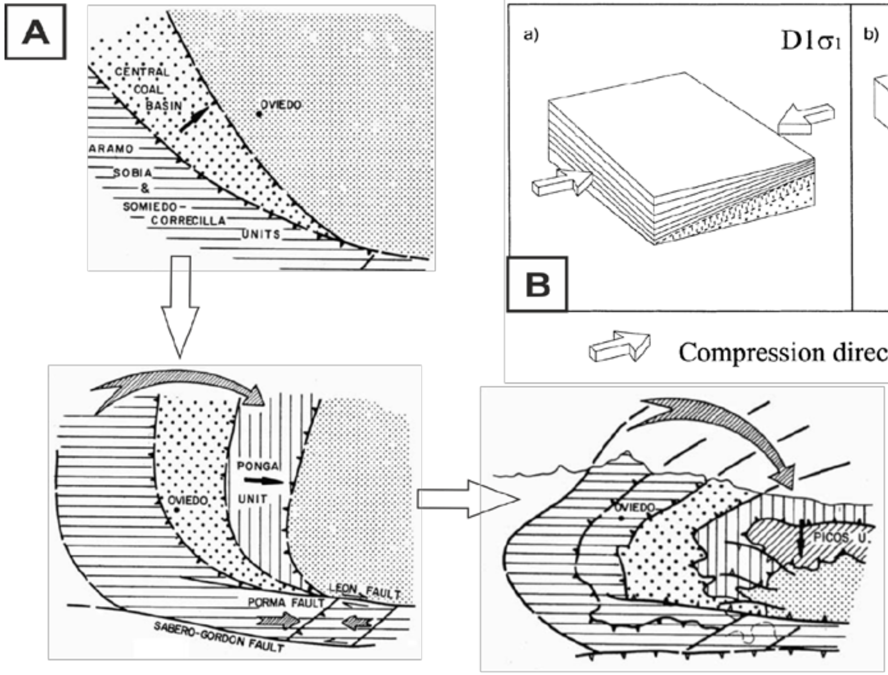
6.2.1. Formation of the Ibero-Armorican Arc

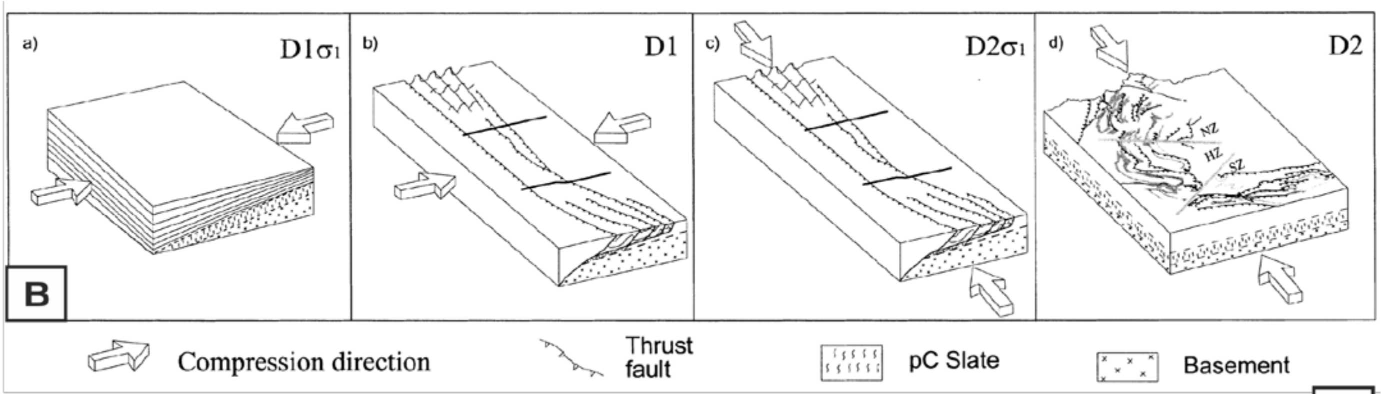
Origins for the arcuate shape of the Ibero-Armorican Arc are controversial, its curvature being attributed to either rotational movement of the thrust nappes (Julivert & Arboleya 1984a; 1984b; Pérez-Estaún *et al*., 1988), late bending of a linear primitive belt (Ries &

Schackleton, 1976; Bonhommet *et al*., 1981; Stewart, 1995; Van der Voo *et al*., 1997; Weil *et al*., 2000; Kollmeier *et al*., 2000; Gutiérrez-Alonso *et al*., 2004; Weil, 2006) or a combination of both processes (Perroud, 1986; Hirt *et al*., 1992).

Julivert (1971) and Marcos (1973) demonstrated that the Cantabria-Asturian Arc was a primary, pre-orogenic feature which has undergone secondary tightening and development of radial folds during Variscan orogeny development (i.e., two phase development). Studies of kinematic indicators and thrust sheet emplacement mechanisms by Julivert & Arboleya (1984a; 1986), supported this theory with slight modification regarding the location of the rotation centre within the arc. Conversely, Brun & Burg (1982) and Pérez-Estaún *et al*., (1988) described a continuous deformation of progressive rotational thrust displacements propagating from west to east (Figure 6.3a). A second theory examines the syn-orogenic indentation of a rigid block with the resulting arc curvature. This rigid block has been suggested to originate from a unique microplate (e.g., Riding, 1974; Matte & Ribeiro, 1975; Lorenz & Nichols, 1984) or from a Gondwanan or Avalonian promontory (e.g., Bachtadse & Van der Voo, 1986; Martínez-Catalán, 1990; Ribeiro *et al*., 1995; 2007; Simancas *et al*., 2005; 2009).

Palaeo-magnetic studies, where declination deviation followed the shape of the arc, indicated a secondary nature of at least half the present curvature, proving it to be an orocline (i.e., a structure with two distinctly different deformation phases; Carey, 1955; Bonhommet *et al*., 1981, Perroud & Bonhommet, 1981; Perroud, 1986; Hirt *et al*., 1992; Marshak *et al*., 1992; Parés *et al*., 1994; Stewart, 1995; Van der Voo *et al*., 1997; Kollmeier *et al*., 2000). Investigations by Parés *et al*., (1994) indicate late tightening of a partially curved (ca. 50%) fold-thrust belt, leaving amounts of prior structural rotation unknown.





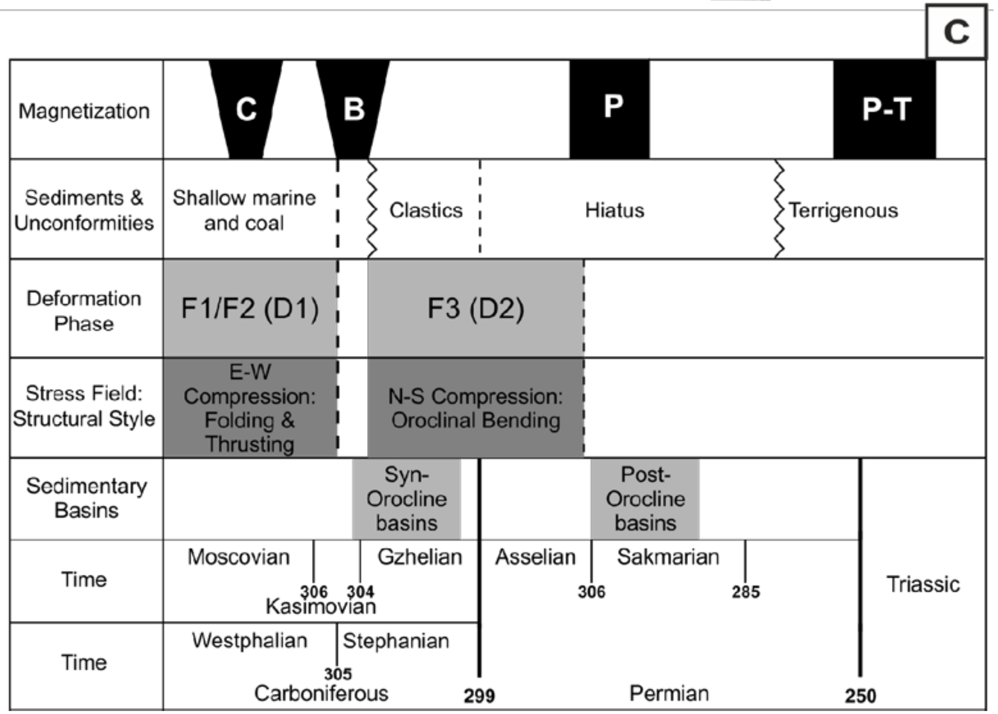


Figure 6.3: (A) Continuous deformation of progressive rotational thrust displacement propagating from west to east as proposed by Pérez-Estaún *et al.*, 1988. **(B)** Block diagrams summarising the evolution of arc tightening beginning with east-west horizontal compression acting on a stable margin (a), resulting in an arc geometry (b) after D1 folding and thrusting. Later north-south horizontal compression (D2) shown in (c) leads to clockwise bending in northern zone (NZ), radial folding in hinge zone (HZ), and tightening of thrusts in southern zone (SZ) of present-day arc geometry. (Adapted after Kollmeier *et al.*, 2000). **(C)** Variscan deformation history of the Cantabrian-Asturian Arc according to Weil *et al.*, (2000; 2001). Deformation is represented by three deformation phases (F1, F2 and F3), their accompanying stress field, sedimentary history and recorded remagnetisation (C = Late Carboniferous; B = Early Permian; P-T = Permo-Triassic). Zigzag lines mark unconformities (Adapted after Dias & Ribeiro (1993); Weil *et al.*, (2000, 2001); Gutiérrez-Alonso *et al.*, 2012).

Based on palaeo-magnetic data, Weil *et al*., (2000; 2001 and 2010) describe three folding phases (Figure 6.3b; 6.3c). The authors assumed that present-day curved geometries were created by interference of original north-south trending structures (first and second folding phases) with a third superimposed folding phase (Figure 6.3c). Older folding phases were dated as Namurian to Stephanian (i.e., Bashkirian and Serpukhovian to Gzhelian), whereas younger phases were Early Permian in age. Consequently, overall shortening direction changed from east-west in the Carboniferous to north-south in the Permian (in present day coordinates; Figure 6.3b; 6.3c). Oroclinal bending around a vertical axis occurred in the Late Stephanian (Gzhelian) to Early Permian over a short (10 to 15 Ma) period (Parés *et al*., 1996; Weil *et al*., 2000; 2001; 2010; Gutiérrez-Alonso *et al*., 2004; Pastor-Galán *et al*., 2011; Johnston *et al*., 2013).

6.2.2. Cantabrian Zone deformation and development

The Cantabrian Zone incorporates the core of the Ibero-Armorican Arc (Figure 6.2), representing the easterly-directed Variscan foreland fold-and-thrust belt (also called the Cantabria-Asturian Arc). The geology of the region is well documented on 1:50,000-scale maps of the Instituto Tecnológico GeoMinero de España (e.g., Lobato *et al*., 1984, Matas & Rodríguez Fernández, 1984; Alonso, 1989; Alonso *et al*., 1989; 1991; Álvarez-Marrón *et al*., 1989; Bastida & Gutiérrez, 1989; Marquinez, 1989; Suárez Rodríguez *et al*., 1990) and older maps, mostly contributed by geologists from Leiden University (e.g., Savage & Boschma 1980).

The Cantabrian Zone was deformed at shallow crustal levels without significant metamorphism. Penetrative cleavage has been suggested by Hirt *et al*., (1992), García Lopéz *et al*., (1997) and Bastida *et al*., (1999) to be developed only locally and is interpreted as being generally of pressure-solution origin. Furthermore, cleavage development has been suggested by Aller *et al*., (1987) to not display any relationship to compressional structures. Deep seismic reflection profiles of the North Iberian crust (e.g., ESCI-N1 and ESCI-N2; Estudio Sísmico de la Corteza Ibérica Norte; Pérez-Estaún *et al*., 1988) show subhorizontal to gently dipping reflective bands corresponding to Cantabrian Zone detachments, with southward and westward dips close to 3° terminating three to five kilometres below the surface (Pérez-Estaún *et al*., 1988; 1994; 1995; 1997; Pulgar *et al*., 1995; Gallastegui *et al*., 1997; Pedreira *et al*., 2003; Fernández-Viejo & Gallastegui, 2005; Diaz *et al*., 2009; Fernández-Viejo *et al*., 2009).

The Palaeozoic succession was strongly deformed during Variscan times by sets of imbricate thrusts, cogenetic folds and late, high-angle faults (Figure 6.4; Ábalos *et al*., 2002). Julivert (1971) and Julivert & Marcos (1973) described two main Variscan deformation phases in the Cantabrian Zone:

(i) First was caused by east-west compression (in present-day coordinates), causing thrust initiation related to the formation of longitudinal folds, characterised by horizontal fold axis and steep axial surfaces parallel to arc curvature

(ii) Second phase marked by radial sets of folds with steep fold axis and associated with the final tightening of the Cantabrian-Asturian Arc.

Structural map patterns of the Cantabrian Zone result from interference interactions between thrust sheets, early arcuate (longitudinal) folds and older radial folds cross-cutting the first fold set (Julivert, 1971; Julivert & Marcos, 1973; Veselovský, 2004; Figure 6.4b). These structures accommodated oroclinal bending by local and regional thrust rotations and the formation of conical folds during final tightening of the Cantabrian-Asturian Arc (Julivert & Marcos, 1973; Julivert & Arboleya, 1984a; Álvarez-Marrón & Pérez-Estaún, 1988; Weil, 2006; Pastor-Galán *et al*., 2012; Figure 6.5).

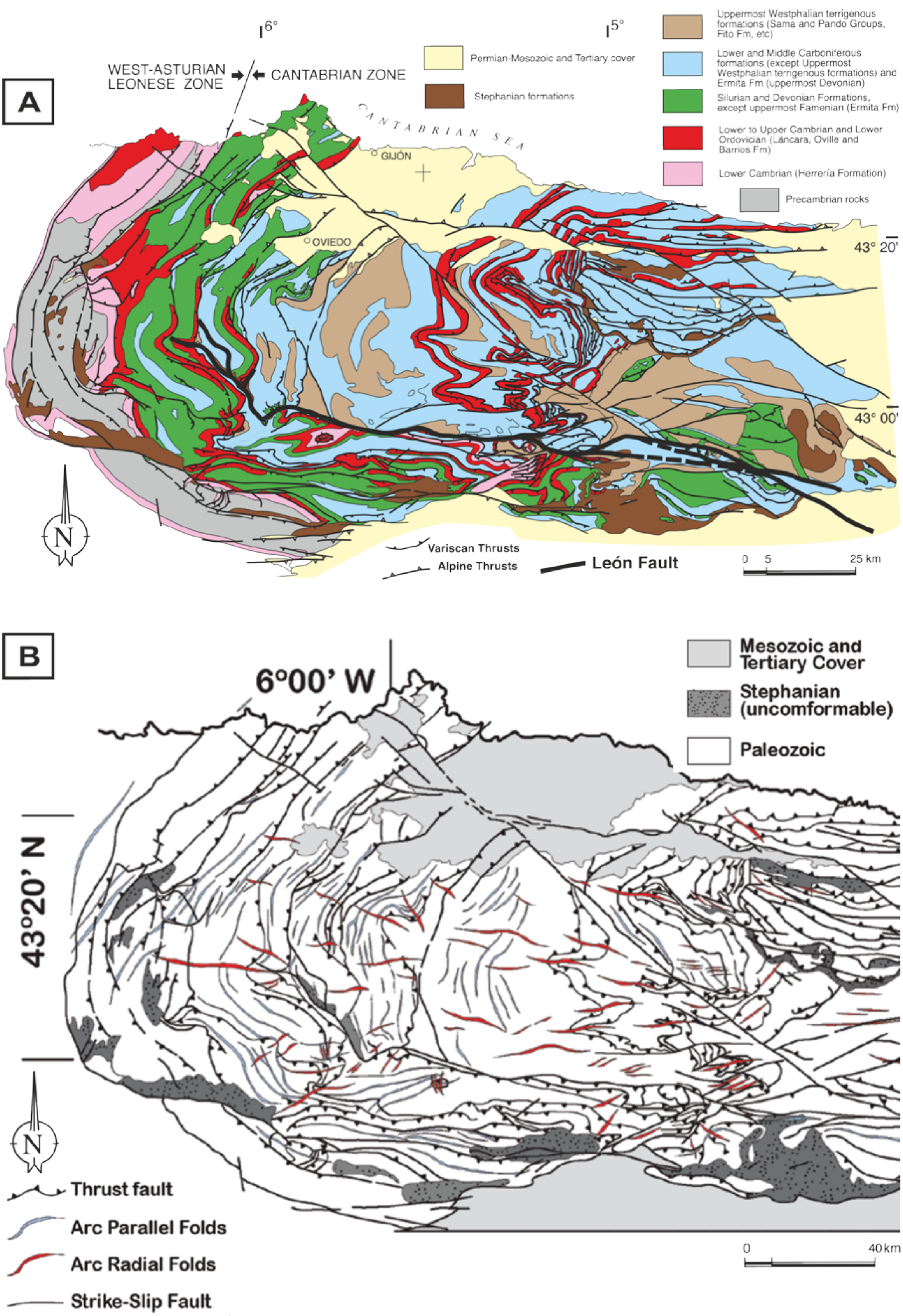


Figure 6.4: (A) Geological map of the Cantabrian Zone. Location of major regional structures, such as the León Fault are identified. (Adapted after Alonso *et al*., 2009). **(B)** Simplified structural map of the Cantabrian Orocline, highlighting the geometry of major thrusts and the orientation of major folds. Two major fold suites identified (i.e., arc parallel and arc radial) (Adapted after Gutiérrez-Alonso *et al*., 2012).

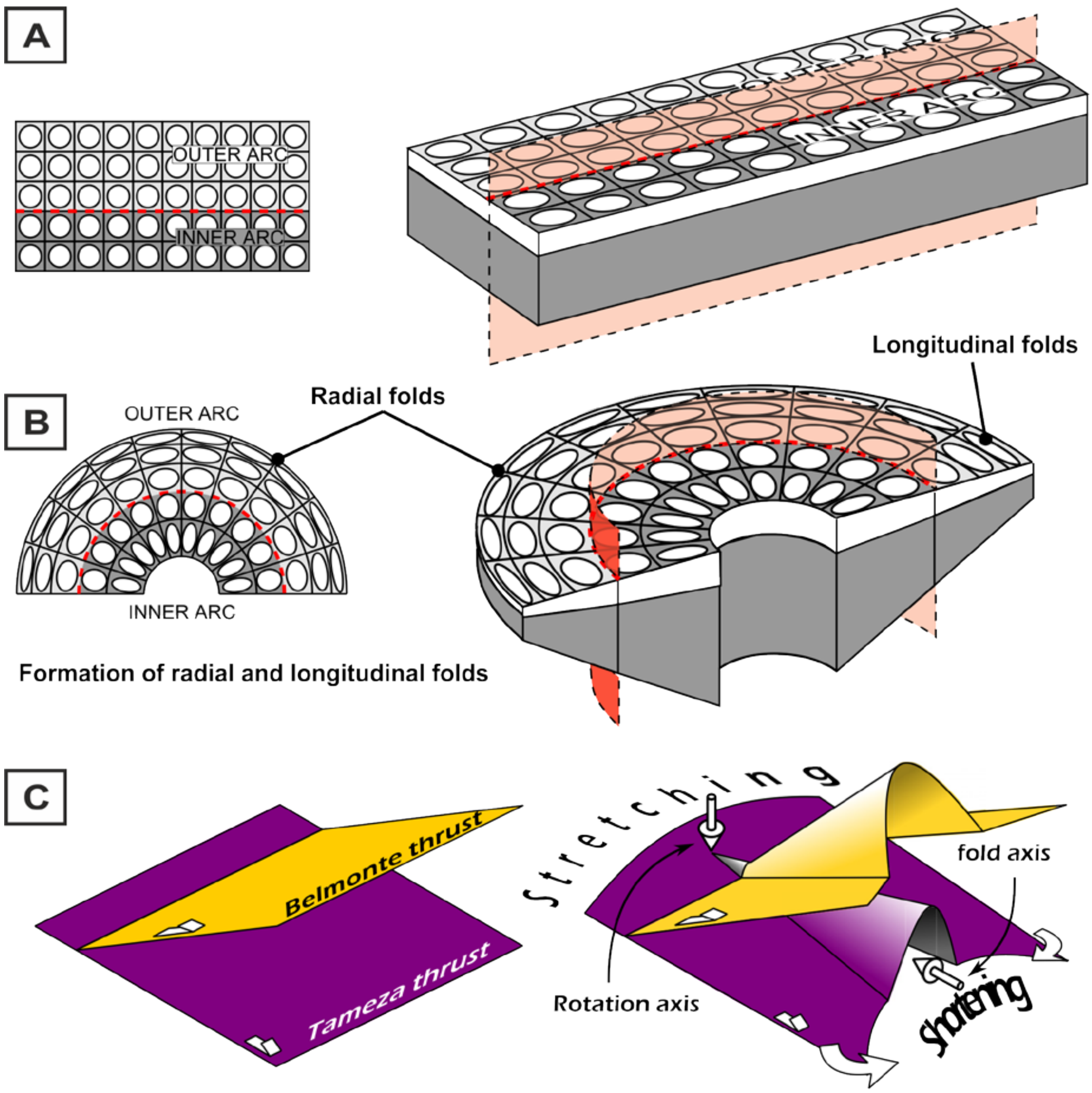


Figure 6.5: (A, B) Effect of lithospheric bending around a vertical axis and the resulting tangential longitudinal strain (Adapted after Gutiérrez-Alonso *et al*., 2004). Arc-parallel shortening of strain ellipses produce arc-parallel (longitudinal) folds, whilst radial (conical) folds are produced as a result of lateral shortening along the arc core. **(C)** Stereographic projection of the Belmonte and Tameza thrusts, Somiedo Unit, depicting a conical fold (Pastor-Galán *et al*., 2012).

Within the Cantabrian Zone, the Namurian (i.e., Serpukhovian Period [322 Ma]) marked the onset of thrust tectonics and the emplacement of thrust sheets in the westernmost part of the zone. Eastward migration of thrust movements in the Cantabrian Zone is noticeable up until the second deformation phase (i.e., Westphalian to Stephanian Periods; Julivert, 1971; Veselovský, 2004). A later deformation phase reached the Cantabrian Zone in the Early Permian (Pérez-Estaún *et al*., 1988; Quesada, 1991; Veselovský, 2004).

The westernmost Cantabrian unit (i.e., Somiedo-Correcillas Thrust Sheet) was emplaced during the early Westphalian (Moscovian) Period (Alonso, 1987; Dallmeyer *et al*., 1997; Weil *et al*., 2010). The Somiedo-Correcillas Unit (Fold Nappe belt of Julivert, 1971) marks the first occurrence of unmetamorphosed Palaeozoic sedimentary units east of the Narcea Antiform basement core (Gutiérrez-Alonso, 1996). Eastward continuing deformation (forelandward) produced the Sobia-Bodón and Aramo units, the Central Coal Basin, Ponga Unit, and more easterly Picos de Europa and Pisuerga-Carrión provinces during the lower Stephanian (Kasimovian-Gzhelian) Period (Figure 6.2a; Pérez-Estaún *et al*., 1988; Pérez-Estaún & Bastida, 1990; Alvarez-Marrón, 1995; Aller & Gallastegui, 1995; Merino-Tomé *et al*., 2009; Weil *et al*., 2010). Complete unit emplacement occurred over an approximate 15 to 20 Ma time span. Dallmeyer *et al*., (1997) estimated the age of deformation within the Cantabrian Zone as ranging between 310-290 Ma (i.e., Moscovian to the Early Gzhelian Period). Tectonic shortening within the Cantabrian Zone has been suggested by Keller *et al*., (2008) to be within the range of 50 to 75% (i.e., one hundred twenty to one hundred fifty kilometres).

During Alpine orogenesis, the Cantabrian Zone was uplifted and exhumed (Alonso *et al*., 1996; Gallastegui, 2000). The degree to which structures were reactivated during north-south compression is contentious within the literature, with some authors suggesting little deformation occurred with only minor reactivations along several Variscan folds and thrusts (e.g., Pulgar *et al*., 1999; Gallastegui, 2000). Alternatively, Ábalos *et al*., (2002) and Robardet, (2002), indicate that many Variscan structures were reactivated resulting in steepened thrusts and faults, with increased shortening. Therefore the present day structural setting gives only a partial and distorted picture of the Variscan Belt prior to oroclinal bending.

6.2.3. Pertinent lithologies within the Cantabrian Thrust Belt: Somiedo-Correcillas Unit

Compared to the West Asturian-Leonese Zone, which contains eleven kilometres of sediment, the Cantabrian Zone shows a much thinner Lower Palaeozoic sedimentary succession, with thicknesses of only three kilometres (Marcos, 1973; Julivert, 1981; Pérez-Estaún *et al*., 1990; Bastida & Aller, 1992). General lithological subdivisions of the Cantabrian Zone Palaeozoic succession comprise:

(i) Pre-Carboniferous sediments which are deposited on a clastic-carbonate shelf, thickening towards the convex part of the arc

(ii) The Carboniferous succession, which marks a major change in sedimentation, indicating the beginning of the Variscan Orogeny and a change from syn-tectonic to post-tectonic conditions (Marcos & Pulgar, 2002).

A generalised and simplified stratigraphical chart for the Somiedo-Correcillas Unit and the Cantabrian Zone is presented within Figure 6.6. Precambrian to Silurian sedimentary successions are dominated by siliciclastic sediments (e.g., Herrería, Oville, Barrios, Formigoso and San Pedro formations) and several long-term hiati (Veselovský, 2004). The only exceptions are Lower Cambrian carbonates of the Láncara Formation. From the deposition of the Silurian San Pedro Formation onwards, influence of elevated areas within the Cantabrian Zone (i.e., the Cantabrian High) become visible within the stratigraphical record (Veselovský, 2004). During the Devonian period, alternating deposition of carbonates (i.e., Abelgas, Santa Lucía, and Portilla formations) and siliciclastics (i.e., Esla, Huergas, Nocedo, and Fueyo formations) evolved. Each period of carbonate growth, producing major reefs, was subsequently followed by successions of clastic material and new phases of carbonate deposition. The end of the Givetian Period (385 Ma) marked the demise of Devonian reefs within the Cantabrian Zone, manifested in the Frasnian event (García-Alcalde, 1998; García-Alcalde *et al*., 2002).

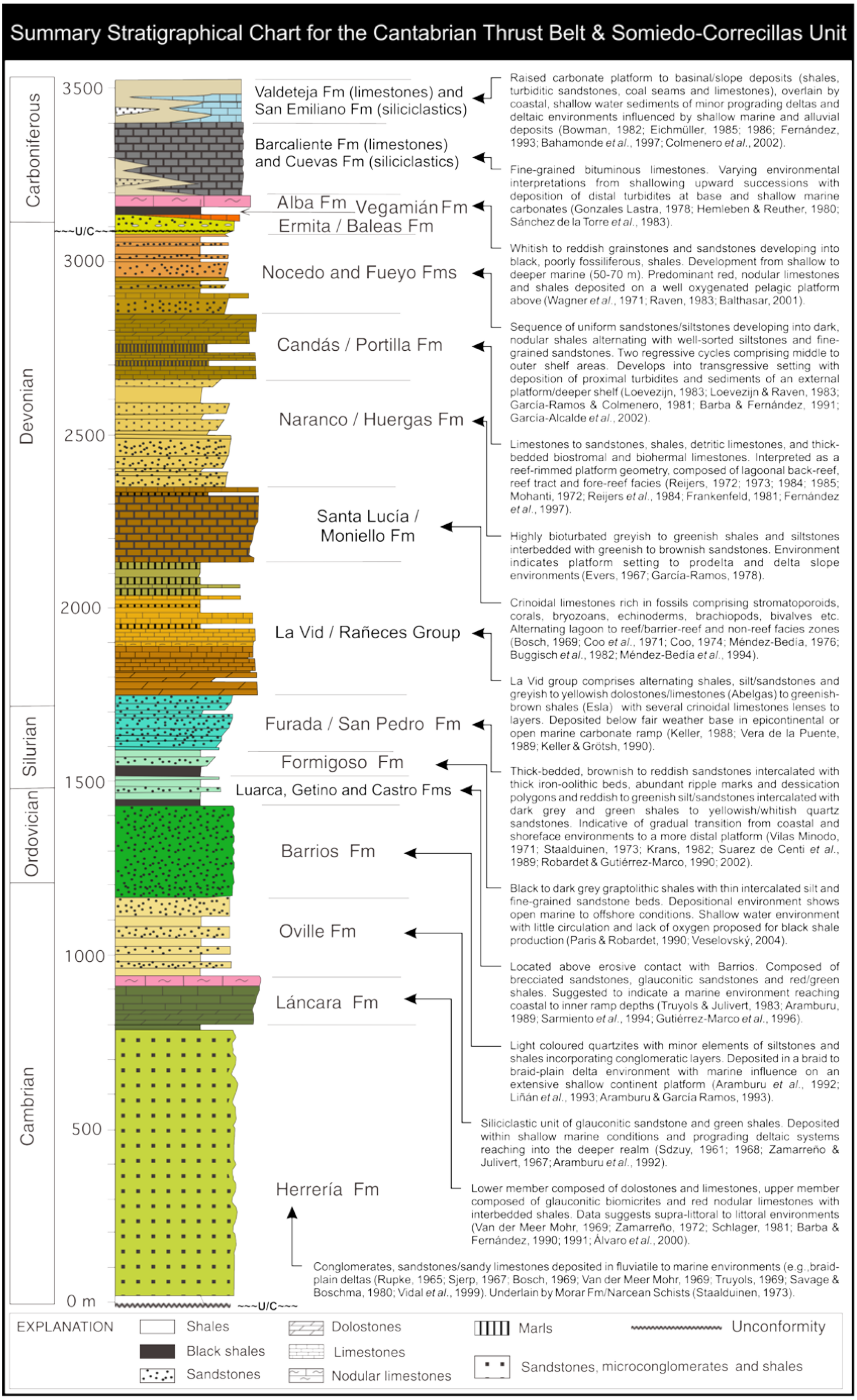


Figure 6.6: Generalised and simplified composite stratigraphical column of the units exposed within the Cantabrian Thrust Belt and the Somiedo-Correcillas Unit. Thicknesses accurate to those identified within the San Emiliano region and the southern Cantabrian Thrust Belt (Adapted after Alonso *et al.*, 2009).

The whole Cantabrian Zone was then subsequently covered by siliciclastics (i.e., Ermita, Balaes, and Vegamián formations) and condensed carbonates of the Alba / Genicera Formation until the Early Namurian (Serpukhovian) Period (Veselovský, 2004). Thick syn-orogenic turbidites (i.e., Olleros Formation), which are initiated in the Serpukhovian Period, mark the onset of the Variscan orogenic phase in the Cantabrian Zone (Colmenero *et al*., 2002). Large carbonate platforms developed (i.e., Barcaliente and Valdeteja formations), which were subsequently covered by terrigenous sediments from the approaching Variscan Orogen (i.e., San Emiliano Formation; Bowman, 1982; Fernández, 1993; Colmenero *et al*., 2002; Marcos & Pulgar, 2002). These successions are overlain in certain areas by unconformable Stephanian successions, which have been interpreted by Nijman & Savage, (1989), Colmenero *et al*., (1996) and Villegas, (1996) as separate pull-apart basins. Thicknesses of the mainly shallow marine Palaeozoic succession range between three thousand eight hundred metres and five thousand metres (Alonso *et al*., 2009). Permian and Mesozoic / Cenozoic age successions in the Cantabrian Zone are mostly removed by erosion, if present at all (Alonso *et al*., 2009). Detailed information regarding lithological ages, thicknesses, divisions and depositional environments is provided within Appendix D.

The Somiedo-Correcillas Unit, and its respective underlying thrust (i.e., Somiedo-Correcillas Thrust), carries all of these lithologies within its hanging-wall with the exception of the Valdeteja Formation limestones and San Emiliano Formation siliciclastics, which dominate the more forelandward Sobia-Bodón Unit. Similarly, the Herrería Formation is not identified within the Somiedo-Correcillas Unit. However, it is included for completeness and its presence in forming dominant structures identified forelandward of the Somiedo-Correcillas Unit, which have pertinence to this current research.

6.2.4. Overview of the Somiedo-Correcillas Unit: Previous research

Previous research within the Somiedo-Correcillas Unit identifies several individual structures highlighting distinct cross-strike structural disparities within the Cantabrian Zone (e.g., along-strike variations in folding and thrusting styles; Julivert, 1971; Pello, 1972; Julivert & Arboleya, 1984a; Pérez-Estaún *et al*., 1988; Alonso *et al*., 1991; Gil-Ibarguchi *et al*., 1991; Alonso & Marcos, 1992; Bulnes, 1995; Ábalos *et al*., 2002; Bulnes & Aller, 2002). These disparities led Kollmeier *et al*., (2000) to divide the Cantabrian Zone within the Cantabrian-Asturian Arc into three domains; a northern, central hinge, and southern zone based on the development of Variscan thrusts prior to oroclinal bending (Figure 6.3b; 6.7; 6.8a).

Within the northern and central hinge zones of the Somiedo-Correcillas Unit, Bulnes (1995) and Bulnes & Aller (2002) identified a fold-dominant zone within which large-scale longitudinal and radial (conical) folds exhibit complex internal structures resulting from thrust emplacement before, during, and after folding (Figure 6.8b [1,2]). These authors suggest that the northern and central zones are dominated by fault-propagation folds which develop northwards from fault-bend folds. According to Alonso (1987) and Pérez-Estaún *et al*., (1988), these fold sets were at least partially caused by the development of duplexes and antiformal stacks, an observation supported by Kollmeier *et al*., (2000), Veselovský (2004) and Weil *et al*., (2010). These folds sets were subsequently tightened during oroclinal bending and thrust sheet rotations (Hirt *et al*., 1992). Transport-directions within these zones indicate transport towards the core of the Cantabria-Asturian Arc (e.g., Bulnes & Marcos, 2001; Alonso *et al*., 2009).

Recent work by Pastor-Galán *et al*., (2012) within the Somiedo-Correcillas Unit identified two sets of thrusts, the first within the regional Cantabrian detachment (i.e., at the base of the Láncara Formation), and a second demonstrating out-of-sequence thrusts with smaller displacement formed by second-phase thrusting or orocline formation. Conical fold development along-strike within the northern and central zones was suggested by Pastor-Galán *et al*., (2012) to be complicated by pre-existing lateral ramps developed prior to oroclinal bending.

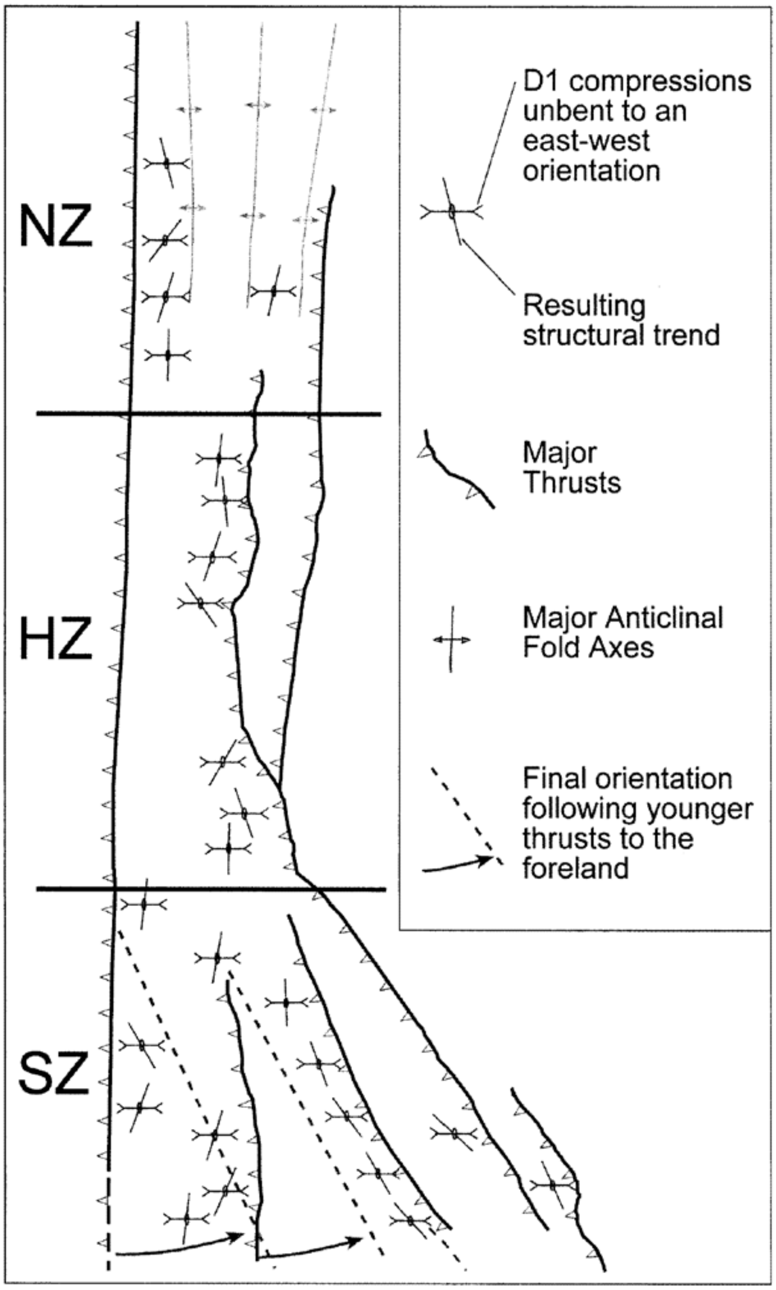


Figure 6.7: Arc geometry during Variscan east-west compression within the Somiedo-Correcillas Unit (Kollmeier *et al*., 2000). Northern zone (NZ) dominated by longitudinal folds, which develop southwards through the hinge zone (HZ) into original north-south trending thrusts within the southern zone (SZ). These thrusts have subsequently swept eastward in a foreland progressive sequence.

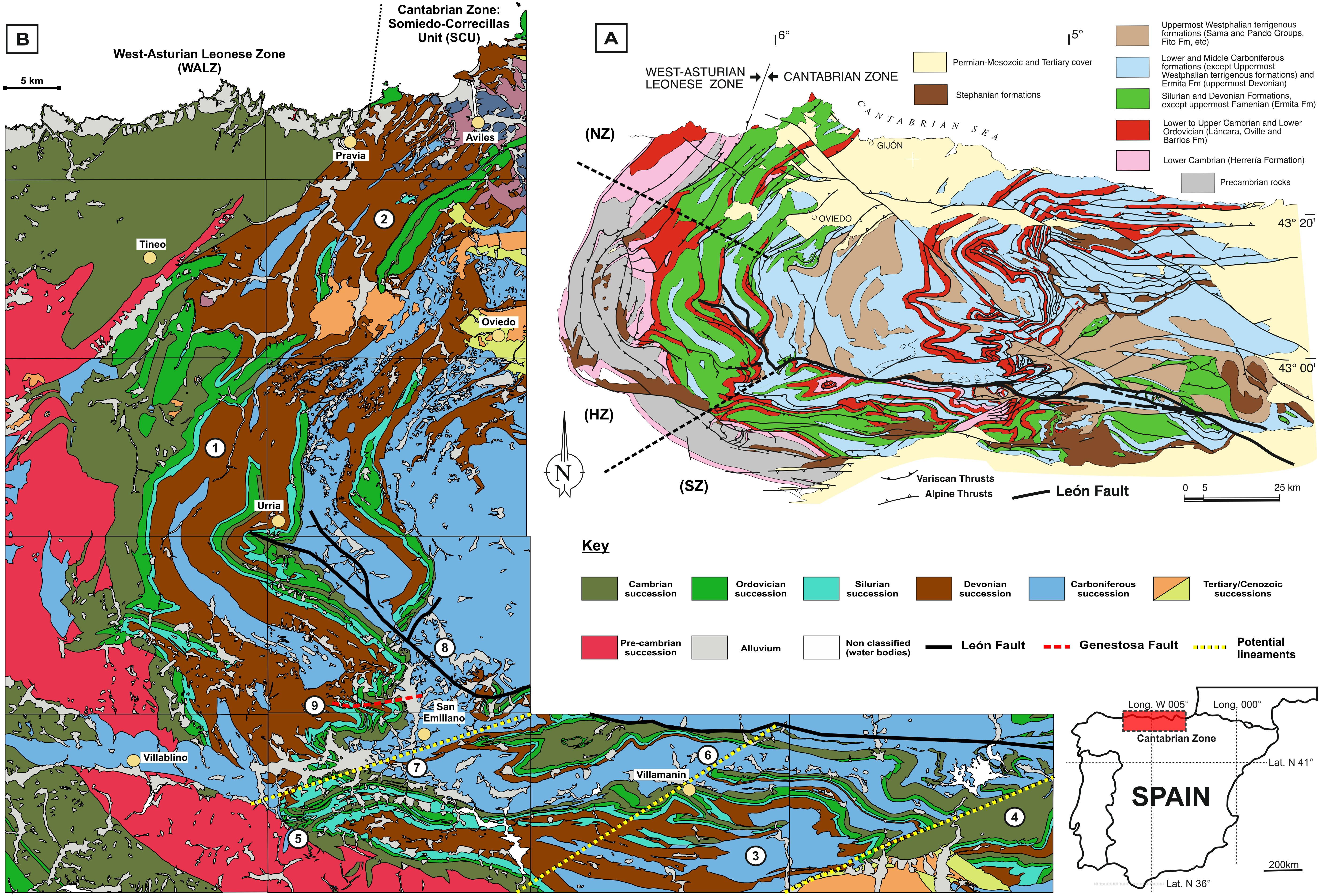


Figure 6.8: **(A)** Geological map of the Cantabrian Zone highlighting Pre-cambrian to Tertiary cover lithologies, and deformation map-patterns (Adapted after Alonso *et al*., 2009). Major structures such as the León Fault are highlighted, whilst distinct zones (northern zone [NZ]; hinge zone [HZ] and southern zone [SZ]) identified by Kollmeier *et al*., (2000) are demonstrated. **(B)** Simplified geological map of the Somiedo-Correcillas Unit, Cantabria-Asturian Arc, northern Spain, which is dominated by Lower Cambrian to Devonian strata. North-south transition from fold-thrust-dominant southern zone [3] to fold-dominant northern zone suggested [1, 2]. Major items for investigation highlighted include, the León and Genestosa faults [8, 9], whilst a series of potential cross-strike compartments identified by Nijman & Savage (1989) (e.g., Porma [4], Luna [6] and Aralla [7]) are also incorporated. Geological maps simplified from MAGNA (1:50;000-scale) map series of the Instituto Tecnológico GeoMinero de España (e.g., Lobato *et al*., 1984, Matas & Rodríguez Fernández, 1984; Alonso, 1989; Alonso *et al*., 1989; 1991; Álvarez-Marrón *et al*., 1989; Bastida & Gutiérrez, 1989; Marquinez, 1989; Suárez Rodríguez *et al*., 1990.

Conversely, basin architecture of the southern arm of the Cantabrian-Asturian Arc is characterised by thrust-dominant, thin-skinned tectonics with main décollement horizons located at the base of the Herrería and Láncara formations, with minor décollements within higher stratigraphical horizons (e.g., Soler, 1967; Julivert, 1971; Pello, 1972; Julivert & Arboleya, 1984a; Pérez-Estaún *et al*., 1988; Alonso *et al*., 1991; Gil-Ibarguchi *et al*., 1991; Alonso & Marcos, 1992; Ábalos *et al*., 2002; Figure 6.8b [3]). Transport-directions within this southern arm suggest a 'piggy-back' mechanism, highlighting a forward-breaking sequence of thrust sheets (Alonso *et al*., 2009). Geometries are characterised by overlapping ramp anticlines, curved ramps, imbricated systems, duplexes and anticlinal stacks (Mitra, 1986; Veselovský, 2004).

Nijman & Savage (1989) identified that a remarkable feature of the southern Cantabrian thrust belt is its variation along-strike. In the east, parts of isoclinally folded thrust sets are exposed (Figure 6.8b [4]); whilst in the west up to five thrust sheets have developed in a thinner, bevelled Palaeozoic sequence (Figure 6.8b [5]). Nijman & Savage (1989) suggested that this along-strike transformation was partly accomplished by several distinct steps, which compartmentalise the southern Cantabrian Thrust Belt. Compartments were suggested along southwest-northeast orientated lineaments, from east to west; the Guardo, Cea, Porma, Luna and Aralla zones (Nijman & Savage, 1989; Figure 6.8b [4, 6, 7]; 6.9). These compartments have also been suggested to act as depocenters for the development of unconformable Stephanian basin sequences within small pull-apart basins (Nijman & Savage, 1989; Bashforth *et al*., 2010). Continuation of thrust sheets into the north-south striking Sobia and Somiedo nappes was suggested by Nijman & Savage (1989) to be complicated by interference with one of the major east-west lineaments, the Léon Line, which delimits the southern Cantabrian Thrust Belt from the Central Basin to the north (Figure 6.8a; 6.8b [8]).

6.2.4.1. Dominant controlling structures: Léon Fault System

The Leon Line fault system extends east-west for about one hundred fifty kilometres (Figure 6.8b [8]; Veselovský, 2004). De Sitter (1962) was the first to consider the Léon Fault to be a significant palaeographical boundary. He interpreted it as an essential fault line controlling both Devonian and Carboniferous sedimentation and influenced Variscan deformation. This interpretation was followed by fellow geologists from the Dutch Geological Survey and Leiden University (e.g., Rupke, 1965; Sjerp, 1967; Evers, 1967; Raven, 1983; Savage, 1979; Nijman & Savage, 1989). Conversely, geologists of the Oviedo University have considered the Léon Fault to be a late Variscan strike-slip or tear fault of Westphalian to Stephanian age (e.g., Marcos, 1968a; 1968b; Lobato, 1975; Julivert, 1967; 1971; Julivert *et al*., 1977; Aller, 1986; Alonso, 1987; Rodríguez Fernández & Heredia, 1987; 1988 and Rodríguez Fernández, 1991). Julivert *et al*., (1968) interpreted first movements along this fault system to have occurred in the Late Westphalian Period, as a result of the structural development of the Central Coal Basin and Ponga units. These authors also refer to movements during post-Stephanian Period times.

Other authors, such as Kullmann & Schönenberg (1978) and Heward & Reading (1980), suggested the Léon Fault to be a dextral strike-slip fault responsible for the control of sedimentation during the Carboniferous, whilst further authors suggested an initial sinistral strike-slip movement, being reactivated during later structural movements of possibly Permian age as reverse faults (e.g., Marcos, 1968a; Julivert *et al*., 1972; Marcos *et al*., 1979; Heward & Reading, 1980). Pulgar *et al*., (1999) further suggest the possibility of a subsequent reactivation during the Alpidic Orogeny.

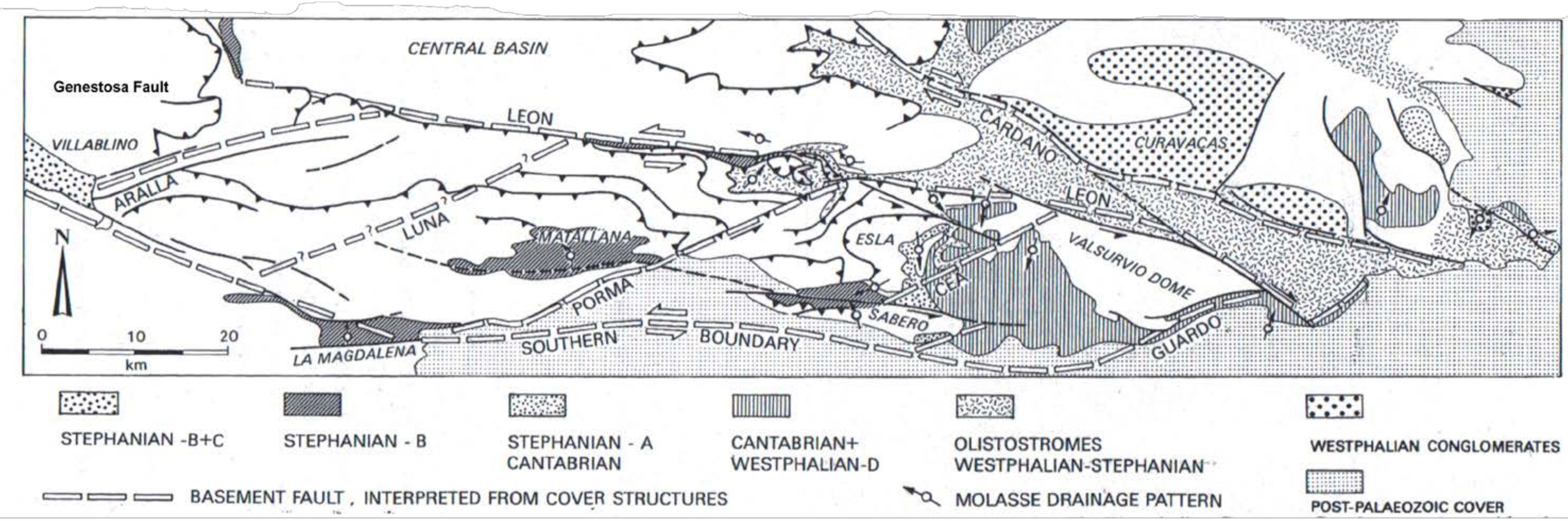


Figure 6.9: Suggested subdivisions of the southern Cantabrian Thrust Belt into compartments by SW-NE orientated structures. From east to west; the Guardo, Cea, Porma, Luna and Aralla lineaments (Adapted after Nijman & Savage, 1989). Location of the Genestosa Fault highlighted.

Alonso *et al*., (2009) suggested that the Léon Fault is in fact a breaching thrust which cross-cuts earlier structures within its footwall, whereas in the hanging-wall it presents some well-development structural flat regions. Breaching displacement along the Léon Fault was suggested to have taken place around the Moscovian (Stephanian) Period boundary (Alonso *et al*., 2009). The Léon Fault / Thrust splits northwards into several branches, a common feature of other major thrusts of the Cantabrian Zone (e.g., Somiedo and Sobia thrusts). This lateral change is attributed to difficulties in thrust propagation northwards from a southern sector dominated by major thrusts to a northern sector where shortening is accommodated by folds or thrust-propagation folds (Julivert & Arboleya, 1984a; 1984b; Alonso *et al*., 1991; Alonso & Marcos, 1992; Bulnes & Aller, 2002). The westernmost splay of the Léon Fault cuts and folds the overlying thrust units, named the Tameza and Somiedo, by way of a thrust-propagation fold within the central hinge region (Figure 6.8b [8]; Alonso *et al*., 2009; Pastor Galan *et al.,* 2012).

6.3. Somiedo-Correcillas Unit fault network analysis: Potential transverse zone identification

Regional analyses for the identification of potential transverse zones within the Somiedo-Correcillas Unit began by defining and compartmentalising along-strike changes in structural style. A detailed fault network and thrust ramp identification analysis of the whole Somiedo-Correcillas Unit was undertaken to identify along-strike changes in structural style and to identify potential thrust ramp alignments within the regional transport direction (i.e., transport oblique / lateral structures; Figures 6.10; 6.11). A series of potential transport-transverse structures are identified within the Cantabria-Asturian Arc (Figure 6.11).

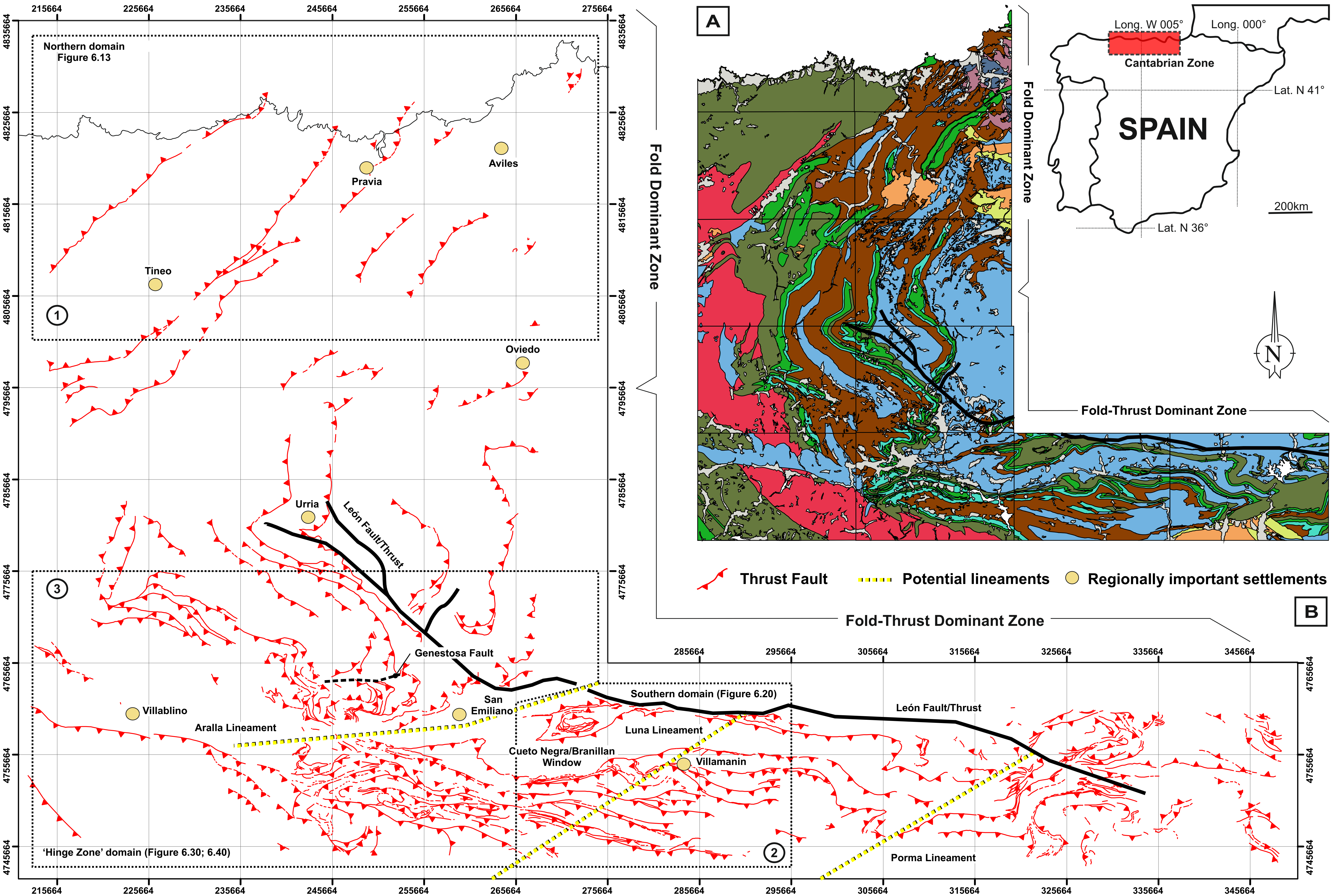


Figure 6.10: (A) Simplified geological map of the Somiedo-Correcillas Unit, Cantabria-Asturian Arc, northern Spain covered by the fault network analysis. **(B)** Thrust fault network within the Cantabria-Asturian Arc, northern Spain. Along-strike structural style variations are identified including, lateral changes from fold-thrust dominant zones (southern arm of the Cantabrian Arc), to fold-dominant zones (northern Cantabrian Arc). León Fault and suggested basement lineaments (i.e., Aralla, Luna and Porma) location taken from Nijman & Savage, (1989) and Alonso et al., (2009). Fault network maps reprojected into UTM Zone 29N.

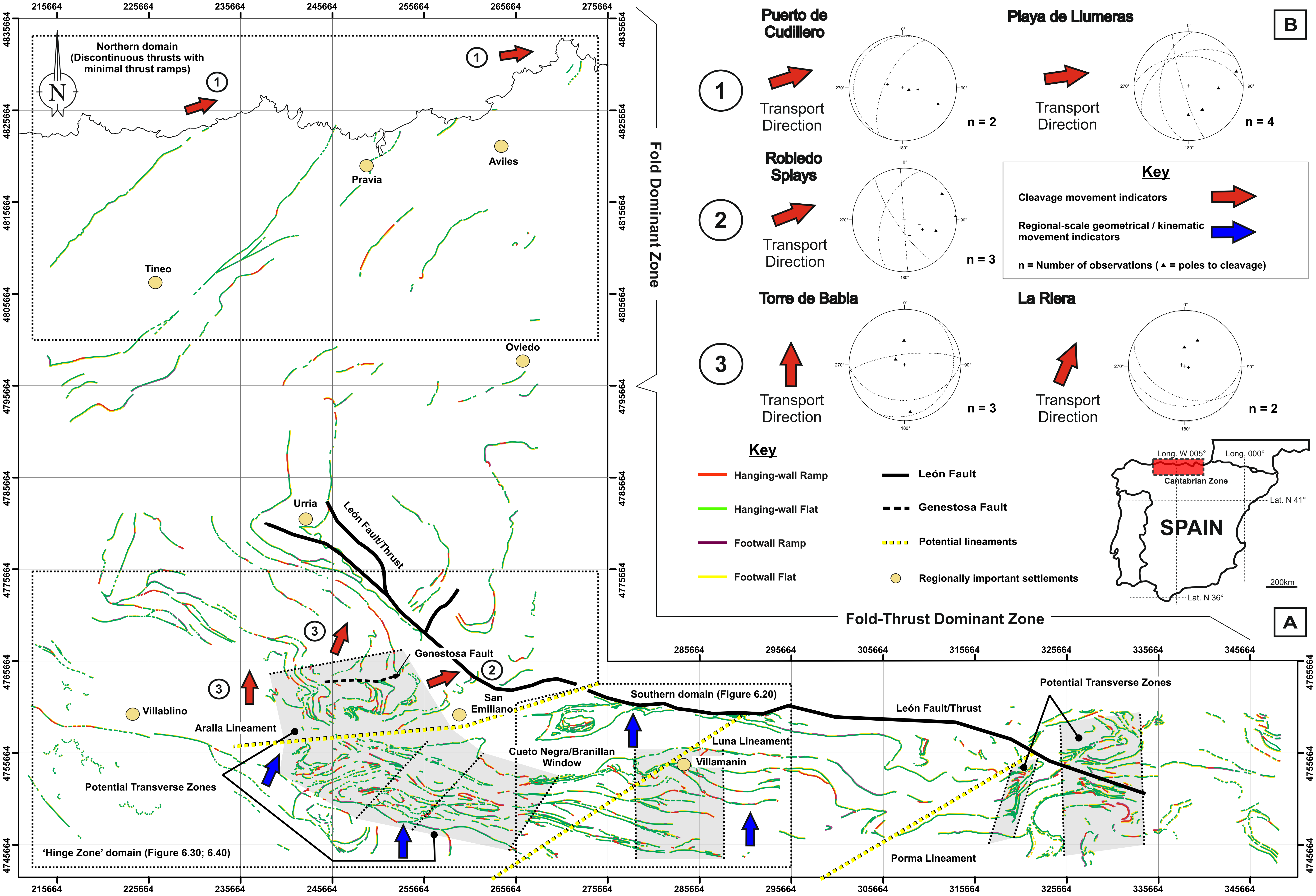


Figure 6.11: (A) Regional fault network analysis of the Somiedo-Correcillas Unit within the Cantabrian Arc, northern Spain, highlighting potential transverse structures. Individual structural analyses of the southern and hinge domains are discussed in greater detail. Northern zone thrust ramp analysis not undertaken due to lack of exposure and discontinuity of thrusts. Fault network maps reprojected into UTM Zone 29N. **(B)** Transport directions (i.e., red arrows) depicted through selected penetrative cleavage movement indicators within the northern and hinge zones (Poles to cleavage presented). Regional-scale kinematic indicators identified during geometrical/kinematic data collection including; thrust and fold architectures, deformation fabrics and deformed quartz veins are highlighted (blue arrows).

Fault network analyses identify a distinct north-south transition from a fold-dominant northern zone (Figure 6.10a; 6.11b [1]) to a fold-thrust dominant southern zone along a transition 'hinge' zone within the San Emiliano region (Figure 6.10a; 6.10b [2, 3]). The Somiedo-Correcillas Unit is subdivided along these divisions into domains (i.e., southern, transition hinge and northern). Small-scale exploratory investigations are focused along the transition from the southern domain at Villamanín to the Bay of Biscay coastline within the northern domain (Figure 6.10). Particular focus is attributed to the transition hinge domain, especially along cross-cutting structures within the San Emiliano region (i.e., Genestosa Fault; Figure 6.8 [9]; 6.10).

6.3.1. Somiedo-Correcillas Unit: Northern domain

The northern domain of the Somiedo-Correcillas Unit is dominated by map patterns highlighting thick stratigraphical successions developing northwards from fault-bend and fault-propagation fold map-patterns (e.g., Urria region; UTM 29N, 4395 7849; Figure 6.8b [1]; 6.12a) supporting the observations of Bulnes & Aller (2002). Thrusts are not laterally continuous within map-view from the northern hinge domain and are generally poorly exposed due to vegetation cover within the Asturian region (Figure 6.10b [1]; 6.12b). Where thrusts are identified, they are separated by thrust sheets averaging 4.75 kilometres, comprising predominantly Ordovician to Devonian strata (i.e., Oville to Portilla formations; Figure 6.10b [1]).

Due to this lack of along-strike thrust continuity, thrust ramps identified within fault network architectural analyses cannot be implemented to identify potential transverse zones (Figure 6.11a [1]). Furthermore, limited exposure and accessibility of units within the northern zone restrict kinematic indicator data collections to the Bay of Biscay coastline.

Figure 6.12: **(A)** Northern zone of the Somiedo-Correcillas Unit dominated by fault-bend and fault-propagation folds which highlight original east-west (Variscan) deformation event followed by later repositioning during oroclinal bending. **(B)** Geometric and kinematic observations within the northern zone, comprising the Asturian region, limited by accessibility and collection of corroborative deformation indicators.

Map-patterns and observations along the Bay of Biscay coastline indicate that the thrust décollement horizon rises northwards from the Lower Cambrian Láncara Formation within the transition hinge domain, into Silurian San Pedro Formation lithologies. Only the Somiedo Thrust within the Somiedo-Correcillas Unit reaches the Bay of Biscay coastline. Kinematic data is also included from the West Asturian-Leonese Zone (WALZ) further to the west, which brings deeper thrust sheets comprising Herrería lithologies onto Devonian strata of the Somiedo-Correcillas Unit (Figure 6.13). Kinematic data collections from west to east (hinterland to foreland) along this coastline are discussed in greater detail within the following subsections.

6.3.1.1. Puerto de Cudillero: West Asturian-Leonese Zone (WALZ)

Within the Puerto de Cudillero region (UTM 29N, 4596 8283), deeper thrust sheets of the West Asturian-Leonese Zone comprising Herrería lithologies are identified (Figure 6.13a; 6.14a). Units identified within this zone highlight a higher grade metamorphic overprint than those within the Somiedo-Correcillas Unit resulting in a psammitic / phyllitic texture (Figure 6.14b). This texture is overprinted by a penetrative fabric and deformed quartz veins, indicating a top-to-east-northeast transport direction once the 30° rotation of Iberia is removed (Figure 6.14c, 6.14d). Boudinage structures can also be observed locally indicating east-west compression, synonymous with Variscan compression directions (Figure 6.15).

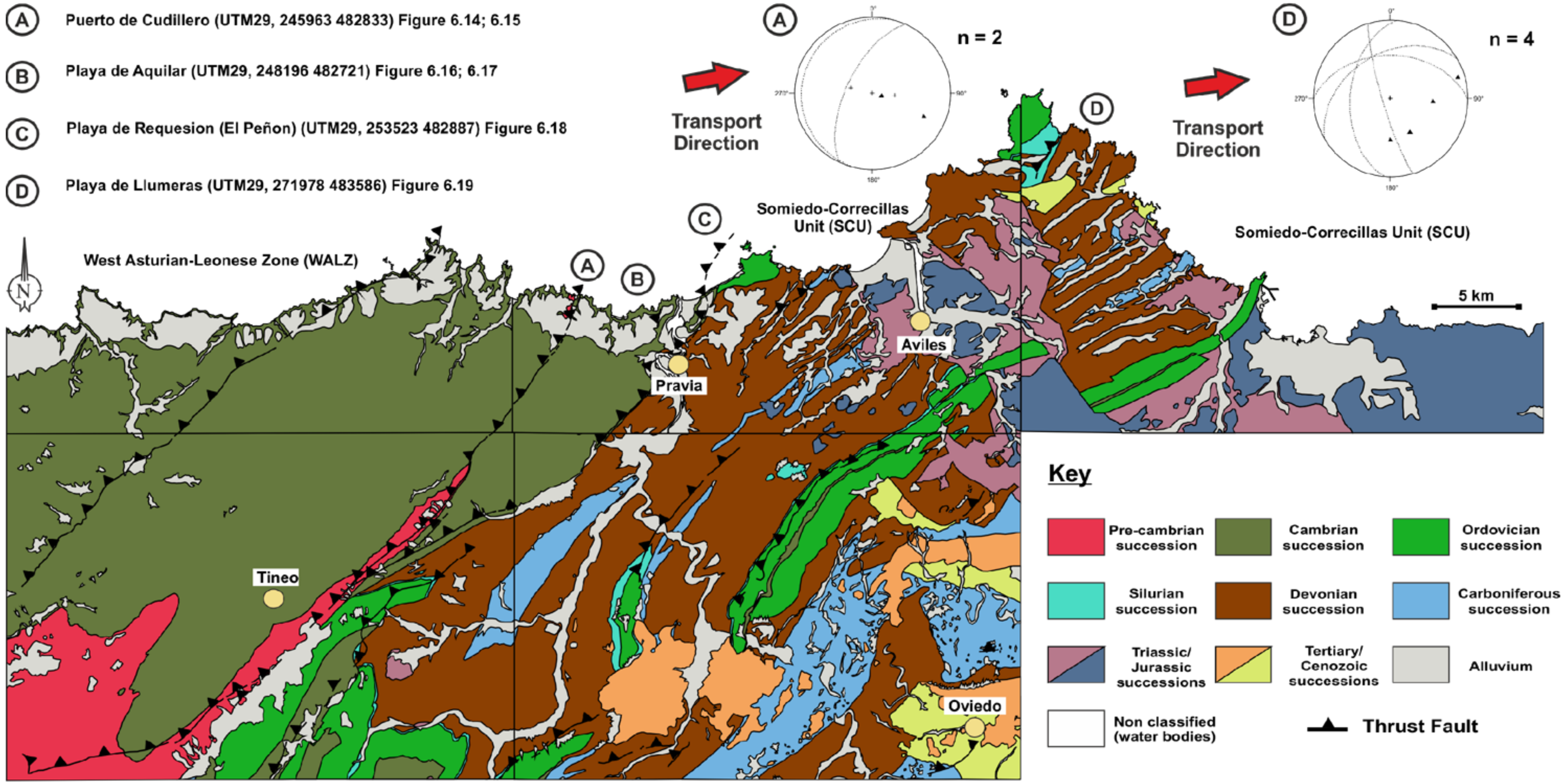


Figure 6.13: Simplified geological map of the Cantabria-Asturian Arc northern domain, highlighting coastal locations where kinematic data was collected. Data sets collected from the West Asturian-Leonese Zone (**A**, **B**, **C**) and the Somiedo-Correcillas Unit (**D**). Transport directions, (i.e., top-to-east-northeast) derived from thrust architectures, deformation fabrics, penetrative cleavages and deformed quartz veins (n = number of observations [poles to cleavage, veins and deformation fabrics]).

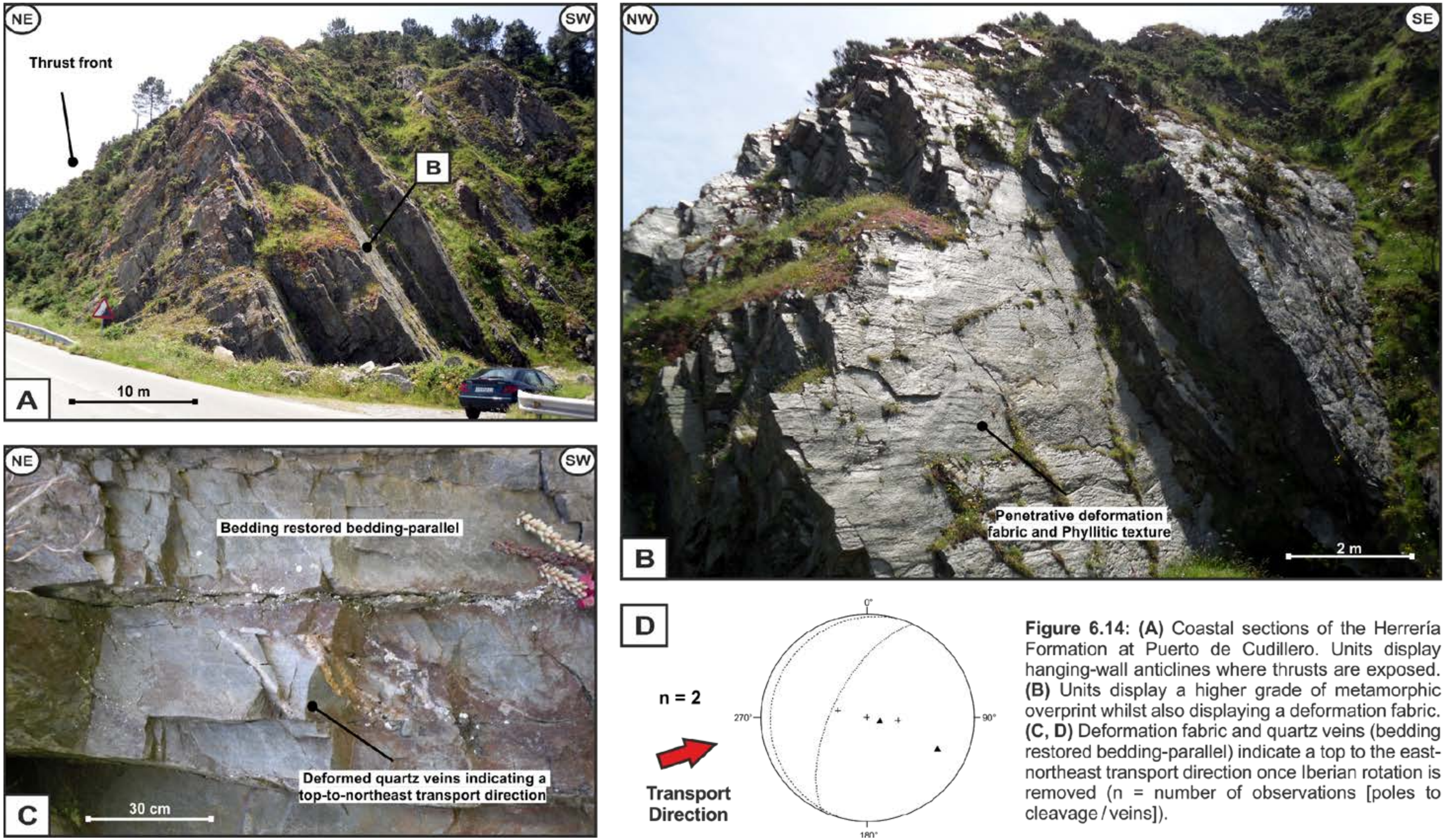


Figure 6.14: (A) Coastal sections of the Herrería Formation at Puerto de Cudillero. Units display hanging-wall anticlines where thrusts are exposed. **(B)** Units display a higher grade of metamorphic overprint whilst also displaying a deformation fabric. **(C, D)** Deformation fabric and quartz veins (bedding restored bedding-parallel) indicate a top to the east-northeast transport direction once Iberian rotation is removed (n = number of observations [poles to cleavage / veins]).

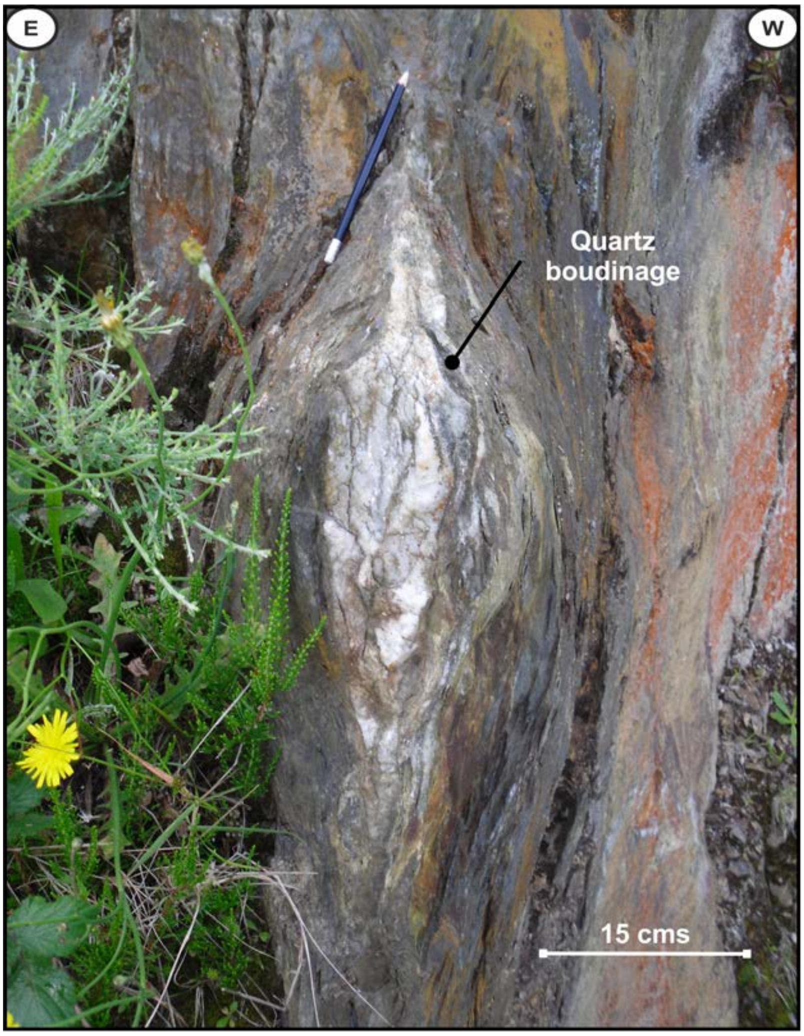


Figure 6.15: Boudinage structure within Herreira units highlighting east-west compression (i.e., Variscan deformation). Pencil applied for scale (15 cms).

6.3.1.2. <u>Playa de Aguilar and Playa de Requesino (El Peñon): West Asturian-Leonese Zone (WALZ)</u>

Further east (forelandward) within the West Asturian-Leonese Zone, further kinematic indicators are identified at Playa de Aguilar (UTM 29N, 4812 8272; Figure 6.16; 6.17). Within the western edge of the beach, large hanging-wall anticlines are identified above a blind thrust fault (Figure 6.16). Units illustrate layer-parallel shear with displacement occurring between individual bedding planes, whilst deformed quartz veins are identified within the thrust translation direction. Deformed quartz veins indicate a present day top-to-west transport direction (Figure 6.16). Within the lower successions of this deformed

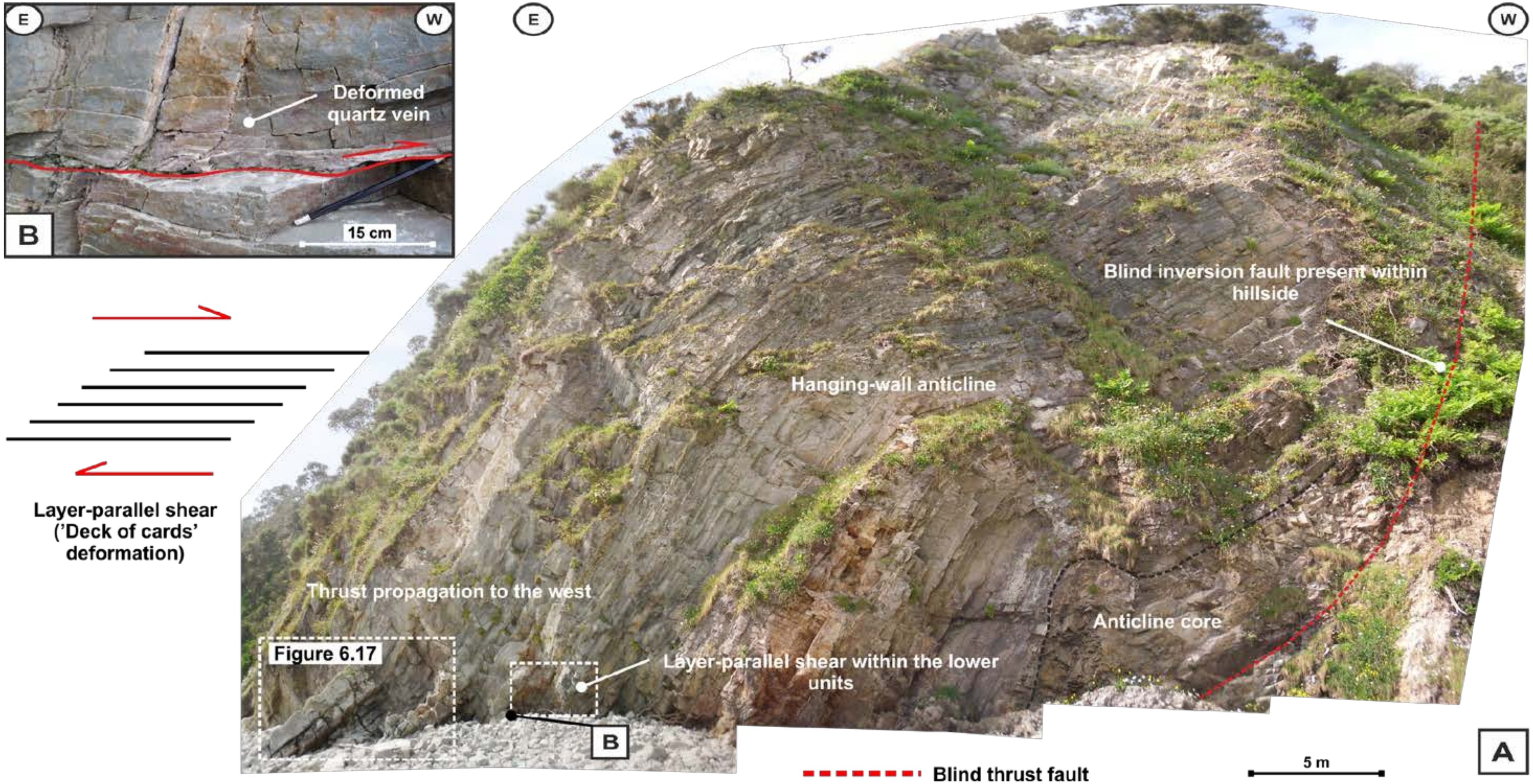
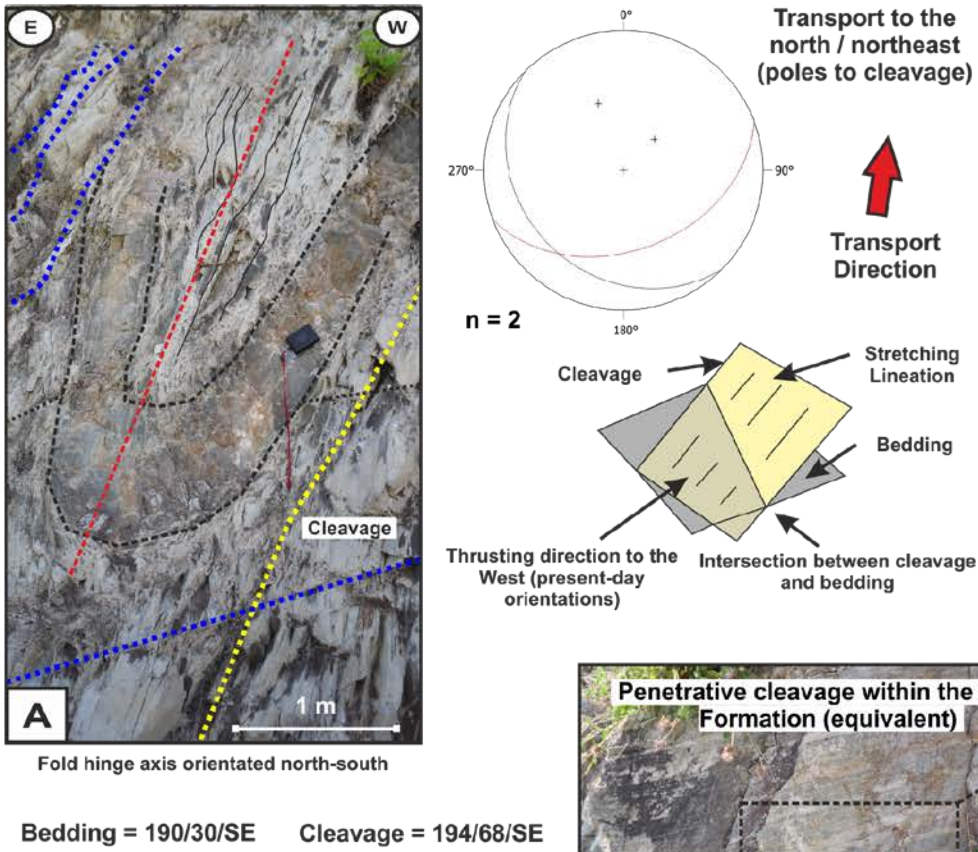


Figure 6.16: (A) Hanging-wall anticlines present within Oville Formation (equivalent) within the West Asturian-Leonese Zone at Playa de Aguilar. Layer-parallel shearing present within lower units indicating that thrust propagation has developed like a deck of cards, resulting in deformed quartz veins (**B**) becoming entrained within the thrust transport direction (image rotated bedding-parallel indicating a present day top-to-west transport). Once bedding is rotated out, a north-to-northeast transport direction is identified. A blind inversion fault is suggested to be present within the vegetated hillside. Units comprise westernmost edge of a northwest-plunging fold within which inversion has occurred along original extensional faults and fold hinges.



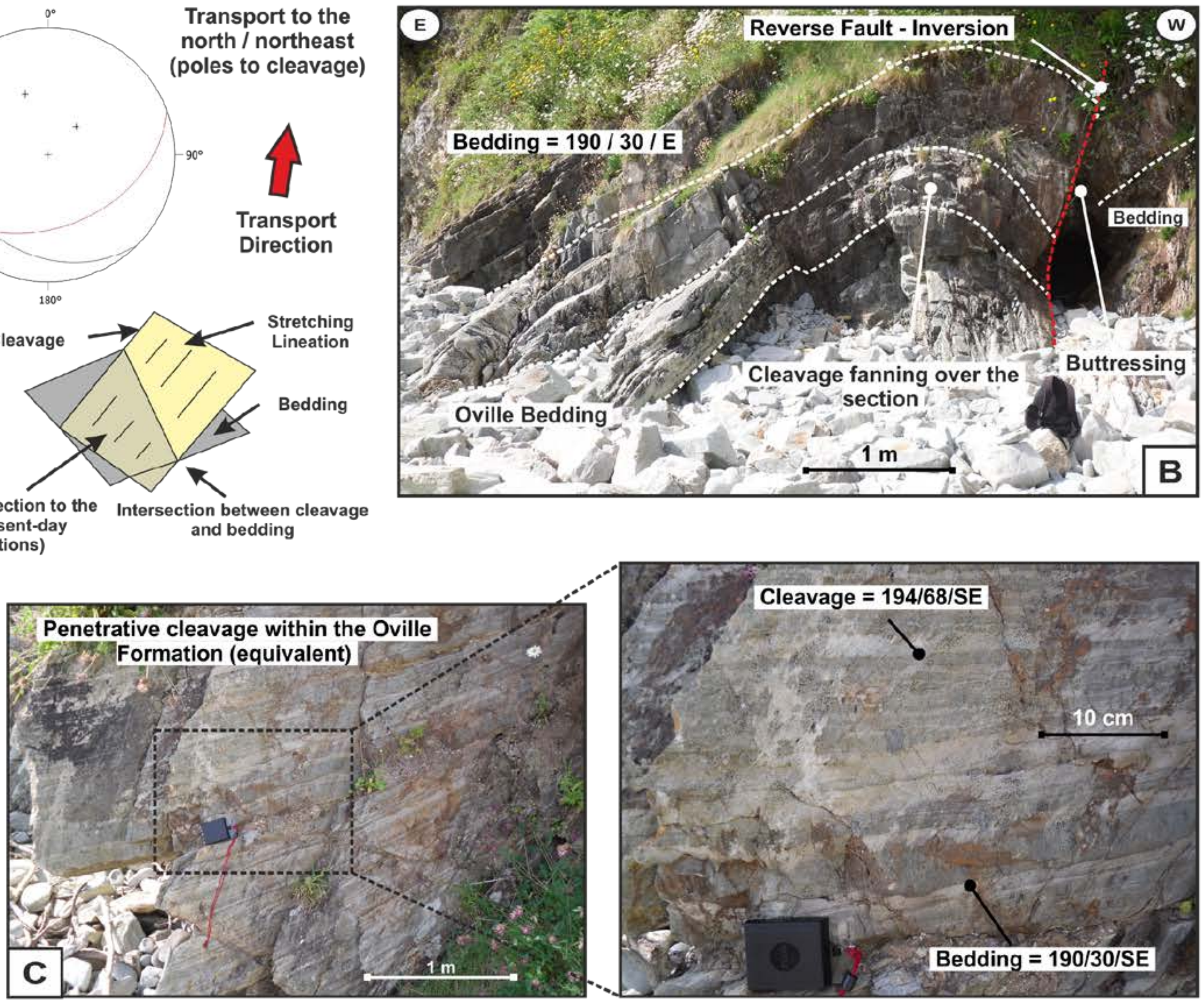


Figure 6.17: (A) Foliated Oville Formation (equivalent) within the Playa de Aguilar coastline **(B)** Buttressing effects (i.e. hanging-wall anticline production) resulting from inversion over a pre-existing extension fault (top-to-west). **(C)** Penetrative cleavage within the Oville Formation (equivalent) indicate a north-to-northeast transport direction (n = number of observations [poles to cleavage]). Stretching lineations also present.

sequence, elements of buttressing against pre-existing extension faults are also identified supporting a present-day top-to-west transport orientation (Figure 6.17a, 6.17b). Penetrative cleavage developed within these higher-grade Oville-equivalent units highlight an original top-to-northeast transport direction once rotation is removed, supporting observations further west within deeper thrust sheets (Figure 6.17c).

On the scale of the Playa de Aguilar beachhead, these units comprise the westernmost end of a north-west plunging syncline within which small to large-scale examples of inversion are identified along original extension faults and fold hinges. Along the El Peñon headland at Playa de Requesino (UTM 29N, 5352 8288), this top-to-east-northeast transport direction is further supported by the most forelandward thrust of the West Asturian-Leonese Zone (Figure 6.18).

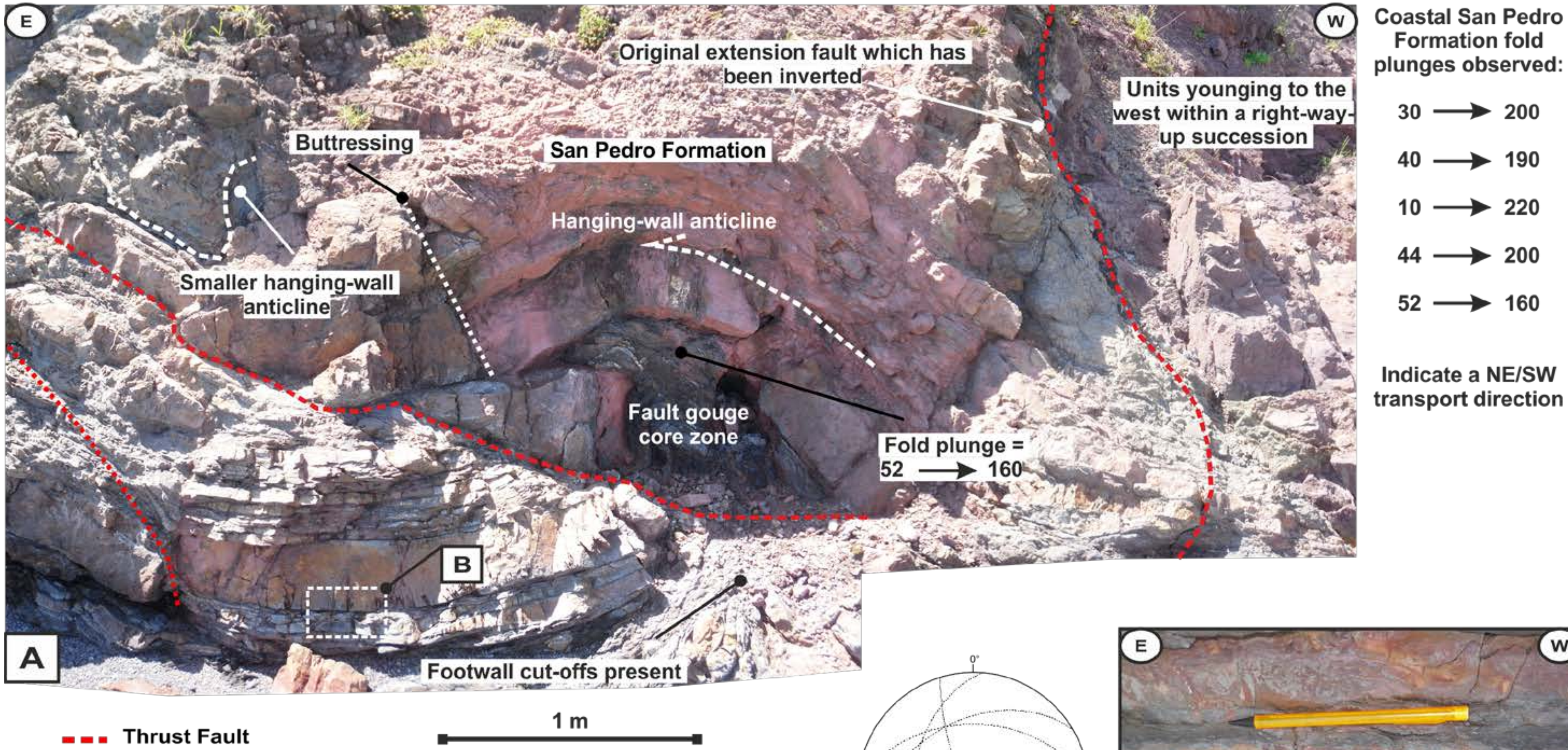
Figure 6.18: Forelandmost thrust of the West Asturian-Leonese Zone at Playa de Requesino (El Peñon) highlighting a top to northeast transport direction. Continuation of thrust lost southwards into the mainland due to vegetation cover.

6.3.1.3. Playa de Llumeras: Somiedo-Correcillas Unit

Within the Somiedo-Correcillas Unit, hanging-wall anticlines are observed along the Playa de Llumeras beach within right-way-up Silurian San Pedro Formation sandstones (UTM 29N,2718 8359; Figure 6.19a). Thrusts along which hanging-wall anticlines develop follow original extension faults within this area, indicating inversion of pre-existing extension faults, an observation supported within the West Asturian-Leonese Zone hinterlandward (westward). Numerous examples of fold plunges within the core of these inverted thrust splays are identified along the Playa de Llumeras beachhead supporting a top-to-northeast transport direction along the Bay of Biscay coastline (Figure 6.19a). Silurian San Pedro Formation sandstones are interbedded with finer-grained laminar-bedded green siltstones. These units display a deformation fabric supporting a top-to-northeast transport direction (Figure 6.19b). Thrust units steepen towards the east and west of the Playa de Llumeras beach (dipping 80° southeast), whilst thrust splays identified along the beach highlight a much shallower angle (40°).

6.3.1.4. Northern domain: Summary

The northern domain of the Cantabria-Asturian Arc is fold-dominant with laterally discontinuous thrusts carrying up to 4.75 kilometres of Ordovician to Devonian stratigraphy within their hanging-walls. Consequently, new methodologies for thrust ramp alignment cannot be implemented. Within the Somiedo-Correcillas Unit, only the main Somiedo Thrust reaches the coastline within Silurian San Pedro Formation sandstones and siltstones indicating an original top-to-northeast transport direction. A regional décollement level rise northwards from Lower Cambrian Láncara Formation dolostones to Silurian San Pedro sandstones is therefore observed within map-patterns. Along the Bay of Biscay coastline, evidence supports the reactivation (i.e., inversion) of pre-existing extension faults where they are aligned 90° to the regional northeast transport direction.



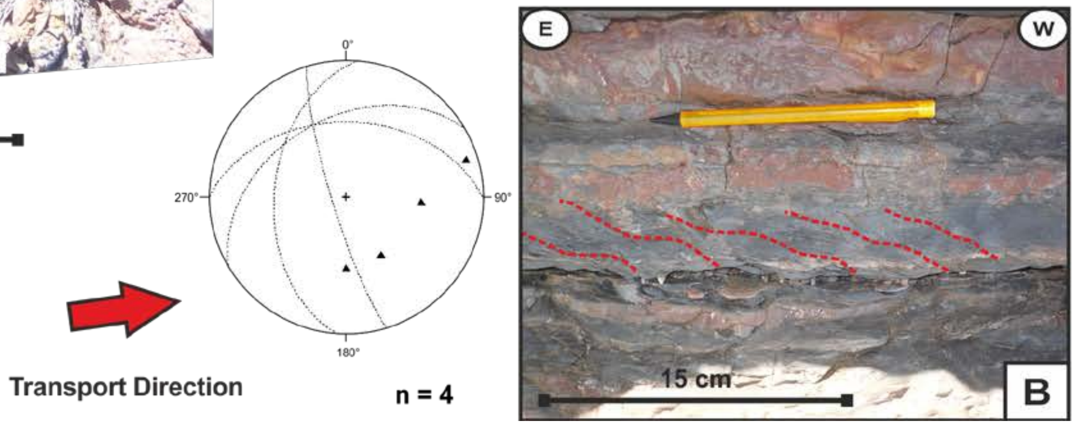


Figure 6.19: **(A)** Thrust faulting within the Somiedo-Correcillas Unit (Siluran San Pedro Formation) at Playa de Llumeras. Units closely linked to pre-existing extension faults developed within the San Pedro Formation. These faults act as pre-existing weakness zones 90° to transport which are subsequently reactivated. **(B)** Penetrative deformation fabrics identified produced during inversion indicate a top-to-northeast thrust translation direction (n = number of observations [poles to thrust planes / deformation fabric]).

6.3.2. Somiedo-Correcillas Unit: Southern domain

The Somiedo-Correcillas Unit southern domain, comprising the La Pola de Gordon map (Figure 6.20a; Alonso *et al.*, 1991), is dominated by a fold-thrust sequence within which localised areas of along-strike complexity are observed within fault network analyses (Figure 6.20b) and stratigraphical separation diagrams (presented hinterland to foreland; Figure 6.23; 6.24). The Somiedo Thrust (i.e., Sole Thrust) highlights several of these along-strike complexities developing westward from two dominant thrust branches within the Las Hoces de Vegacervera (UTM 29N, 9309 7530) and Gete (UTM 29N, 9168 7562) regions (Figure 6.20a [1, 2]), into a single diffuse zone of breaching thrusts within the Embalse de Caseras / Aralla region (UTM 29N, 7457 7559 to 6938 7552; Figure 6.20a [3]). This cross-strike transition is accomplished via a series of sinuous thrusts, fault-propagation folds and antiformal stacks. These along-strike complexities have been previously attributed to the Luna Lineament (Nijman & Savage, 1989).

6.3.2.1. <u>Hoces de Vegacervera to Rodiezmo: Somiedo-Correcillas Unit</u>

Within the easternmost zones of the southern domain, where the Somiedo Sole Thrust branches into two thrust sequences (i.e., Hoces de Vegacervera and Gete), a series of east-west orientated, thrust-breached, synclinal folds are identified producing locally overturned stratigraphical sequences and along-strike thrust ramps within fault network analyses (Figure 6.20a [1]; 6.20b [1]). Map-patterns indicate that thrust ramp development occurs as a result of more than one phase of thrusting. Higher thrust sequences of the Hoces de Vegacervera truncate the underlying Gete Thrust Sheet sequence (Figure 6.20a [1, 4]; 6.20b [1]). Along-strike within the Hoces de Vegacervera branch, Lower Cambrian Láncara Formation dolostone / limestone sequences are thrust over Carboniferous Barcaliente and Valdeteja limestone sequences within the Hoces de Vegacervera hillside (Figure 6.21a). Láncara sequences indicate considerable lateral (east-west) shortening,

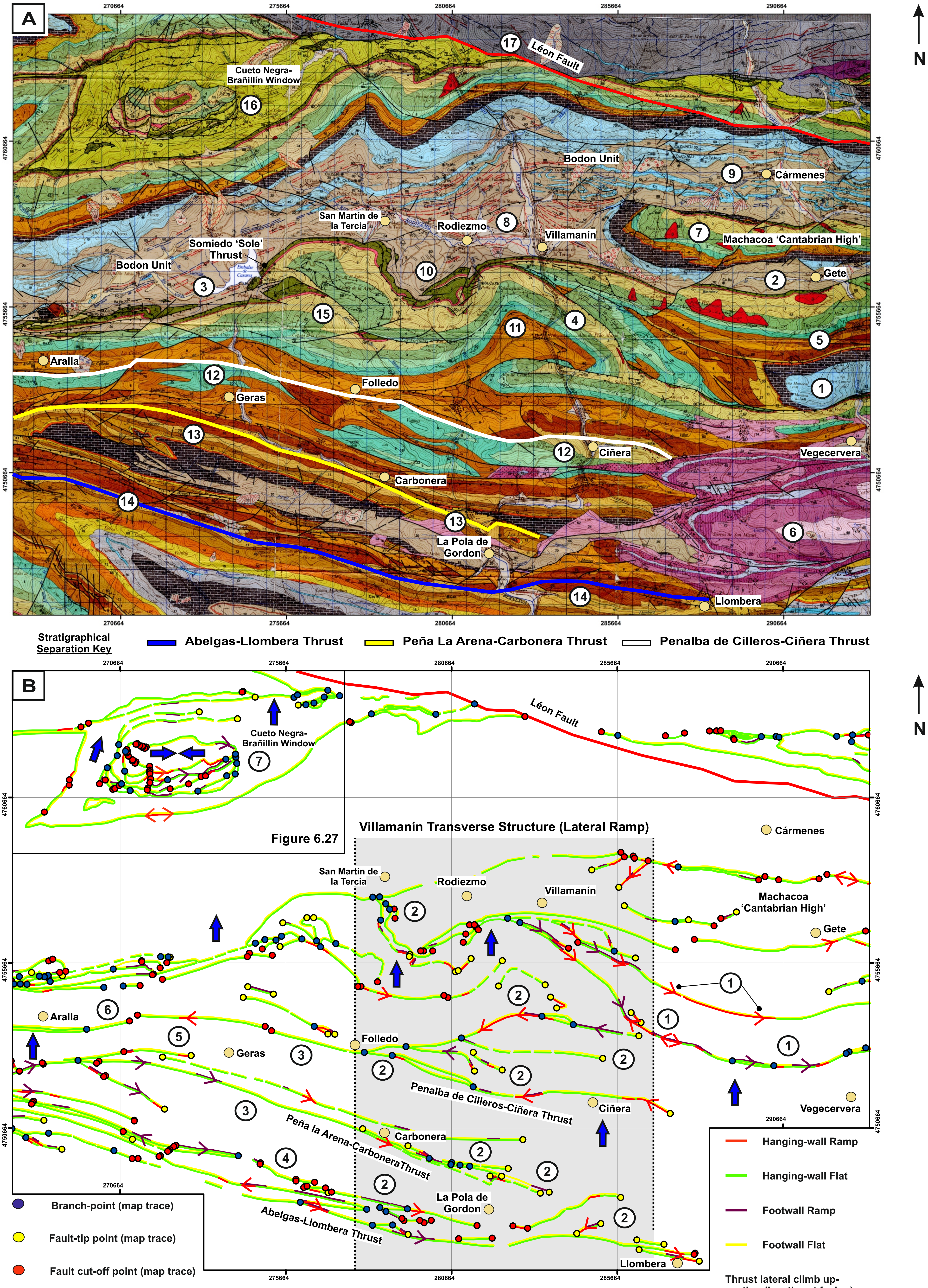


Figure 6.20: (A) La Pola de Gordon geological map (Alonso *et al*., 1991) highlighting distinct map-view cross-strike architectural variations, particularly along the Somiedo Sole Thrust. Lithological descriptions and individual unit colours highlighted within map identified within stratigraphical section (Figure 6.6). **(B)** Fault network analysis of the Pola de Gordon southern domain. Distinct alignments of thrust ramps, thrust bifurcations and fault tip-points within the Villamanín region are identified highlighting a potential sub-decollement structure (i.e., Villamanín transverse structure/lateral ramp). Observations highlighted within the text are numbered, whilst transport kinematics are presented (blue arrows).

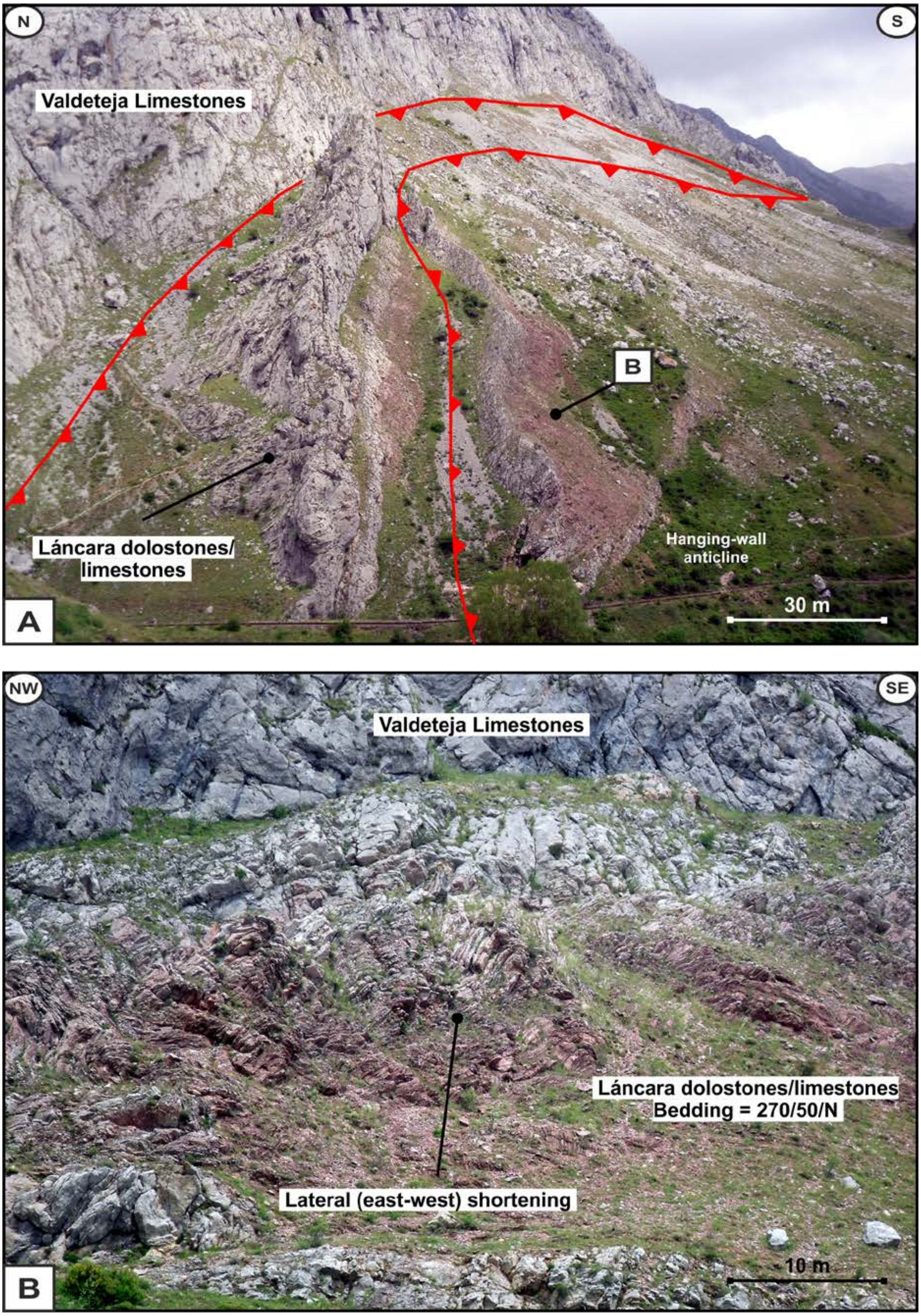


Figure 6.21: (A) Hoces de Vegacervera branch of the Somiedo Thrust within the eponymous hillside. Láncara dolostones / limestones are thrusted over Valdeteja Formation limestones. **(B)** Lateral (east-west) shortening highlighted within the Láncara dolostone / limestone units.

whilst indicating a top-to-north transport direction (Figure 6.21b). Along-strike thrust map-traces are identified cutting-down stratigraphically westward, truncating footwall synclines within the underlying Gete Thrust Sheet, until they join the main Somiedo Thrust southeast of Rodiezmo (UTM 29N, 8144 7568; Figure 6.20a [4]; 6.20b [1]). Synclinal folds developed within the Gete Thrust Sheet are themselves breached along their northern hinges, further supporting a northwards transport (Figure 6.20a [5]). The Gete Thrust Sheet is subsequently truncated out by the Hoces de Vegacervera Thrust Sheet. Hinterland sections of the easternmost Hoces de Vegacervera Thrust Sheet are hidden by unconformable Stephanian sequences of the Matallana Basin (Figure 6.20a [6]). Kinematic development of these sequences suggests that the Gete and Hoces de Vegacervera thrusts comprise inverted original extension faults within which separate basin sequences developed.

Within the Somiedo Thrust foreland, a distinct condensed stratigraphical sequence is identified along the Machacao hillside, comprising the 'Cantabrian High' within the southern arm of the Cantabrian Thrust Belt (Figure 6.20a [7]). A frontal thrust is identified within map-view connecting this condensed sequence to the Somiedo Sole Thrust south of San Martín de la Tercia (UTM 29N, 7846 7576; Figure 6.20a [8]; 6.22a). Within the foreland Bodon Unit, large folds developed within the Valdeteja limestone further indicate a northward transport (Figure 6.20a [9]; 6.22a). No such folds however, are identified within the San Emiliano and Valdeteja formation successions within the hinterland of the Machacao 'Cantabrian High'. Absence of Valdeteja Formation folds within these syn-orogenic sequences may indicate that they have been passively carried on a foreland propagating thrust. Valdeteja Formation folds within the thrust footwall connecting the Machacao 'Cantabrian High' to the Somiedo Sole Thrust are truncated suggesting either out-of-sequence thrusting or later reactivations of the thrust front (Figure 6.20a [8]).

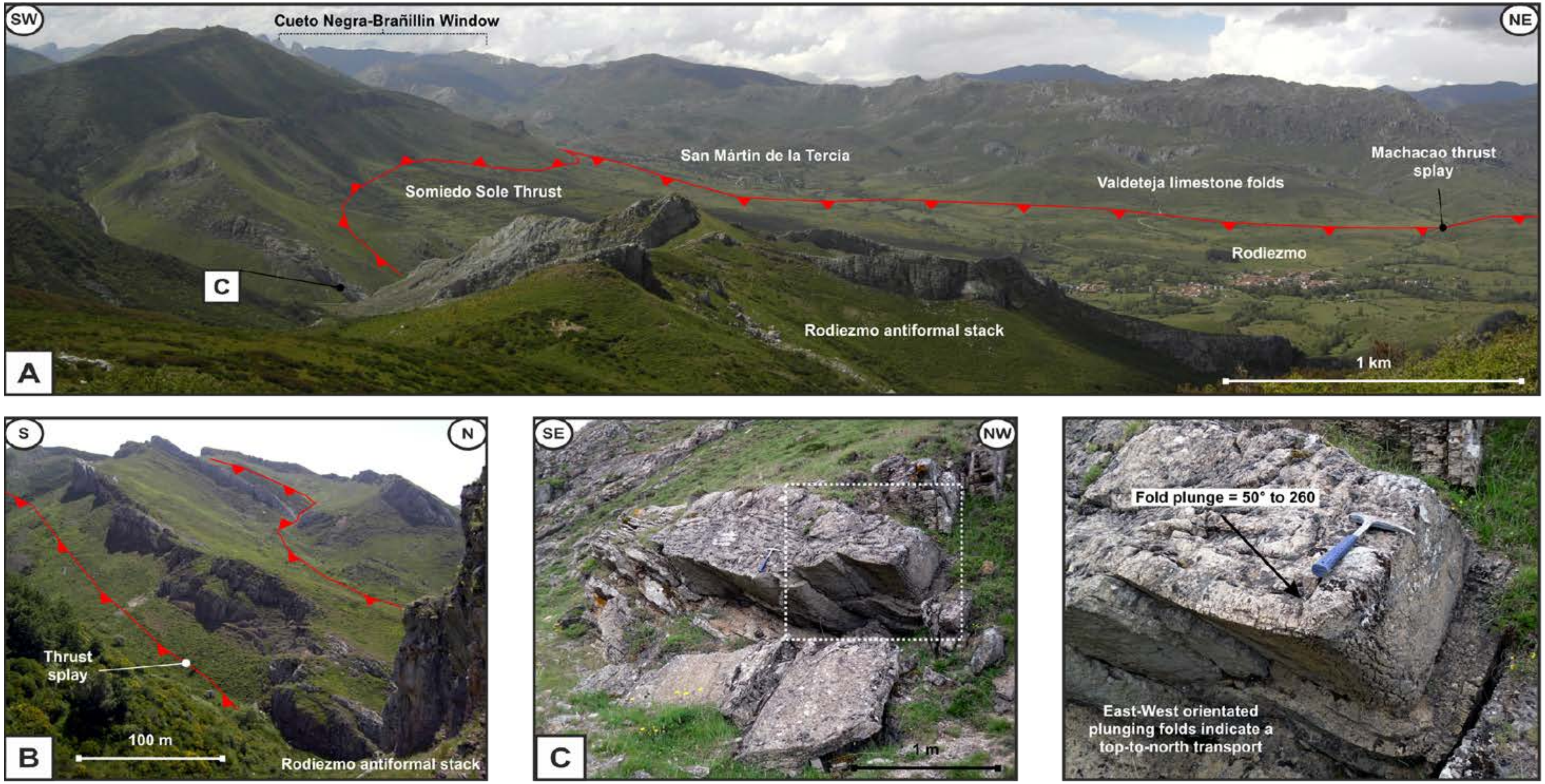


Figure 6.22: (A) Overview of the Rodiezmo Valley facing northwest. Deformation along the Somiedo Sole Thrust is highlighted by the Rodiezmo antiformal stack and the southwards concavity of the Sole Thrust along-strike south of San Martín de la Tercia. Branching thrust connecting the Somiedo Sole Thrust to the Machacao sequence identified. Important frontal structures also highlighted (i.e., Cueto Negra-Brañillín Window). **(B)** Thrust splays within the Rodiezmo antiformal stack highlight a top-to-north transport direction (Kelly, 2008). Deformation structures (i.e., plunging folds) along the Somiedo Sole Thrust within the Láncara sequence further support this interpretation **(C)**.

South of Rodiezmo, a large antiformal stack (termed here the Rodiezmo antiformal stack; Kelly, 2008) is identified (UTM 29N, 8067 7563; Figure 6.20a [10]; 6.22a; 6.22b). Development of this structure indicates a location of buttressing along the Somiedo Sole Thrust, eastward of which, the Somiedo Sole Thrust bifurcates into the Gete and Hoces de Vegacervera branches. Conversely, the Somiedo Thrust to the west bulges one kilometre further into the Rodiezmo valley south of San Martín de la Tercia (UTM 29N, 7855 7576; Figure 6.20a [10]; 6.22a). Kinematic and geometrical data collected within this research, and within previous investigations (e.g., Kelly, 2008), incorporating detailed analyses of thrust splays and folds within the Rodiezmo antiformal stack, indicate a top-to-north transport direction (Figure 6.20a [10]; 6.22b; 6.22c).

Within the hinterland of the Rodiezmo antiformal stack, numerous map-traces of thrust ramps, fault-tips and branch-points are identified with fault network analyses aligned within the northward transport direction (Figure 6.20b [2]). Architectural elements define a zone of thrust fault nucleations and bifurcations which are indicative of a potential sub-décollement transverse structure (Figure 6.20b [2]). Further supportive evidence is identified south of the town of Villamanín, where a large fault-propagation fold is developed within the hanging-wall of the Hoces de Vegacervera Thrust (Figure 6.20a [11]).

Along-strike development of the Rodiezmo antiformal stack, a large-scale fault-propagation fold south of Villamanín, and the potentially inverted frontal structures comprising the Gete and Hoces de Vegacervera Thrust branches are suggested to reside, and develop over the intersection of a pre-thrust frontal and lateral ramp intersection over a potential sub-décollement transverse structure or lateral ramp (termed here the Villamanín Lateral Ramp; Figure 6.20a; 6.20b).

Stratigraphical separation diagrams (presented hinterland to foreland; Figure 6.23; 6.24) depict this potential structure within a series of structurally higher thrusts which breach earlier folds, placing Devonian strata over Carboniferous stratigraphy i.e., the Penalba de Cilleros Ciñera (Figure 6.20a [12]; 6.23b [1]), Peña La Arena-Carbonera (Figure 6.20a [13]; 6.24a [1]), and Abelgas-Llombera (Figure 6.20a [14]; 6.24b [1]) thrusts. These thrusts coalesce westwards into single dominant thrust planes within map-view across the potential Villamanín Lateral Ramp (Figure 6.20b [3]), with the notable exception of the Abelgas-Llombera Thrust (Figure 6.20a [14]; 6.20b [4]), which remains as a diffuse zone of thrusts due to along-strike interactions of relatively competent limestones (i.e., Devonian Santa Lucia limestones) and incompetent siltstones and shales (i.e., Devonian La Vid Group; Figure 6.20a [14]).

Thrusts identified within the Peña La Arena-Carbonera Thrust map-trace north of Pola de Gordon (UTM 29N 8176 7490; Figure 6.20a [13]), indicate that these higher thrust sequences are far travelled, with potentially multiple décollement horizons, and support a multiphase development in which underlying thrust sheets are truncated by structurally higher out-of-sequence thrusts (i.e., breaching thrusts).

West of the Rodiezmo antiformal stack (UTM 29N, 8067 7563) a distinct breaching thrust is identified within the Embalse de Caseras region of the Somiedo Sole Thrust (Figure 6.20a [3]). This breaching thrust truncates the underlying Somiedo Sole Thrust placing San Emiliano siliciclastic units over Lower Cambrian Láncara dolostone / limestone sequences, indicating that an out-of-sequence phase of movement is recorded south of the Rodiezmo antiformal stack into the large fault-propagation fold south of Villamanín (Figure 6.20a [15]). This out of-sequence phase of thrusting may occur as a result of

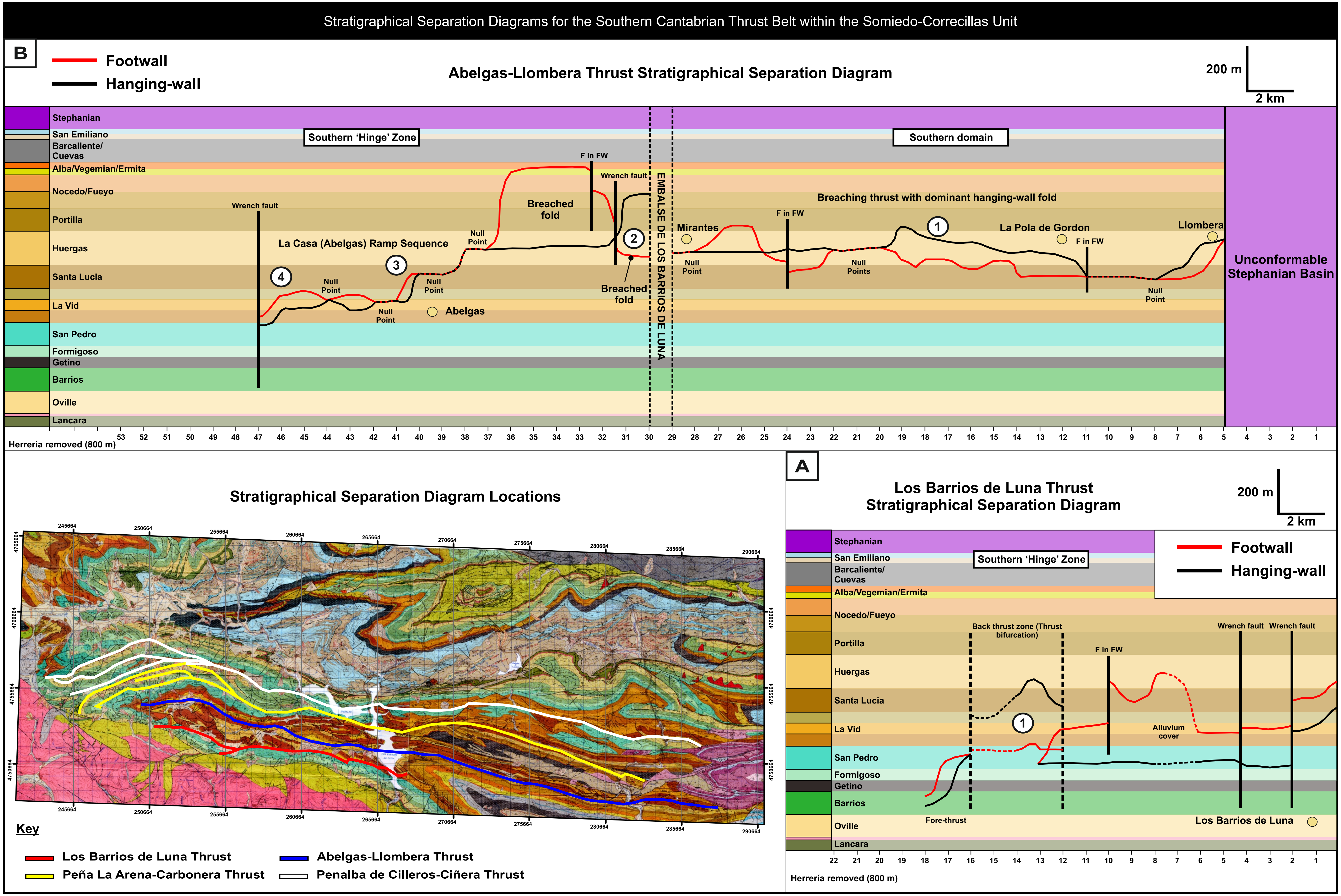


Figure 6.23: Stratigraphical separation diagrams within the Southern Cantabrian Thrust Belt (presented hinterland to foreland, locations highlighted within map) along the Los Barrios de Luna **(A)** and Abelgas-Llombera **(B)** thrusts, highlighting along-strike relationships between thrusts and stratigraphy. Generalised and simplified composite stratigraphical column of units exposed within the Somiedo-Correcillas Unit provided. Thicknesses accurate to those identified within the San Emiliano region and the southern Cantabrian Thrust Belt. Along-strike distances and location of respective regionally-important settlements correlated and corrected to UTM Zone 29N. Observation identified within text numbered.

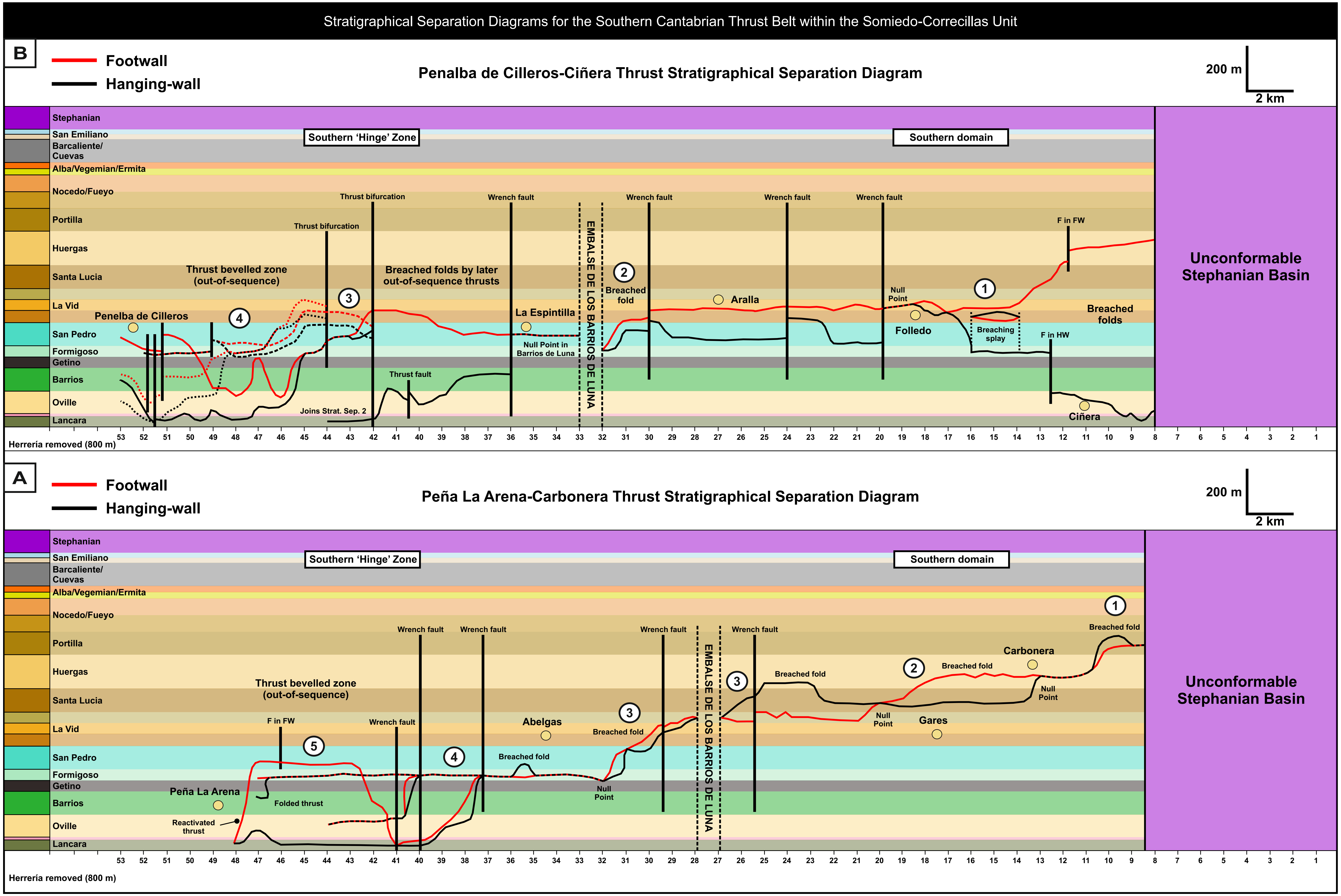


Figure 6.24: Stratigraphical separation diagrams within the Southern Cantabrian Thrust Belt (presented hinterland to foreland. Locations highlighted within Plate 34) along the Peña La Arena-Carbonera **(A)** and Penalba de Cilleros-Ciñera **(B)** thrusts, highlighting along-strike relationships between thrusts and stratigraphy. Generalised and simplified composite stratigraphical column of units exposed within the Somiedo-Correcillas Unit provided. Thicknesses accurate to those identified within the San Emiliano region and the southern Cantabrian Thrust Belt. Along-strike distances and location of respective regionally-important settlements correlated and corrected to UTM Zone 29N. Observation identified within text numbered.

thrust propagation being halted along the Somiedo Sole Thrust during development of the Rodiezmo antiformal stack.

Kinematic indicators (i.e., fault slickensides, sheared fault blocks and plunging folds) within the San Emiliano siliciclastic series, located east of the Embalse de Caseras dam, further support a top-to north transport direction once the near vertical (80°) bedding sequences are restored (Figure 6.25). The Embalse de Caseras region is indicative of a diffuse zone of thrusts, comprising the Somiedo Sole Thrust, which display oscillatory thrusting (i.e., forelandward-hinterlandward-forelandward propagations). A distinct northeast-southwest alignment of thrust bifurcations is highlighted within the Embalse de Caseras region, indicating a potential sub-décollement structure (Figure 6.20b [5, 6]).

Hinterlandward structurally higher thrusts do not highlight this along-strike complexity, with only a few hanging-wall and footwall ramps being produced as a result of earlier folds being breached by later thrusts (Figure 6.20b [5]; 6.24a [2]). This suggests that thrusts within the younger Devonian La Vid strata may be produced within a structurally higher décollement to those within the Somiedo Sole Thrust. This suggestion is supported by map-view thrust spacing observations, which decrease hinterlandward from one and a half to two kilometres within the foreland Somiedo Sole Thrust zone, to hinterland thrusts within Devonian strata which are spaced hundreds of metres apart. This hinterlandward change in décollement could account for the lack of Lower Cambrian to Ordovician strata within map-view, and within stratigraphical separation diagrams, south of the Pena La Arena-Carbonera Thrust (Figure 6.20a [13]; 6.23b; 6.24a).

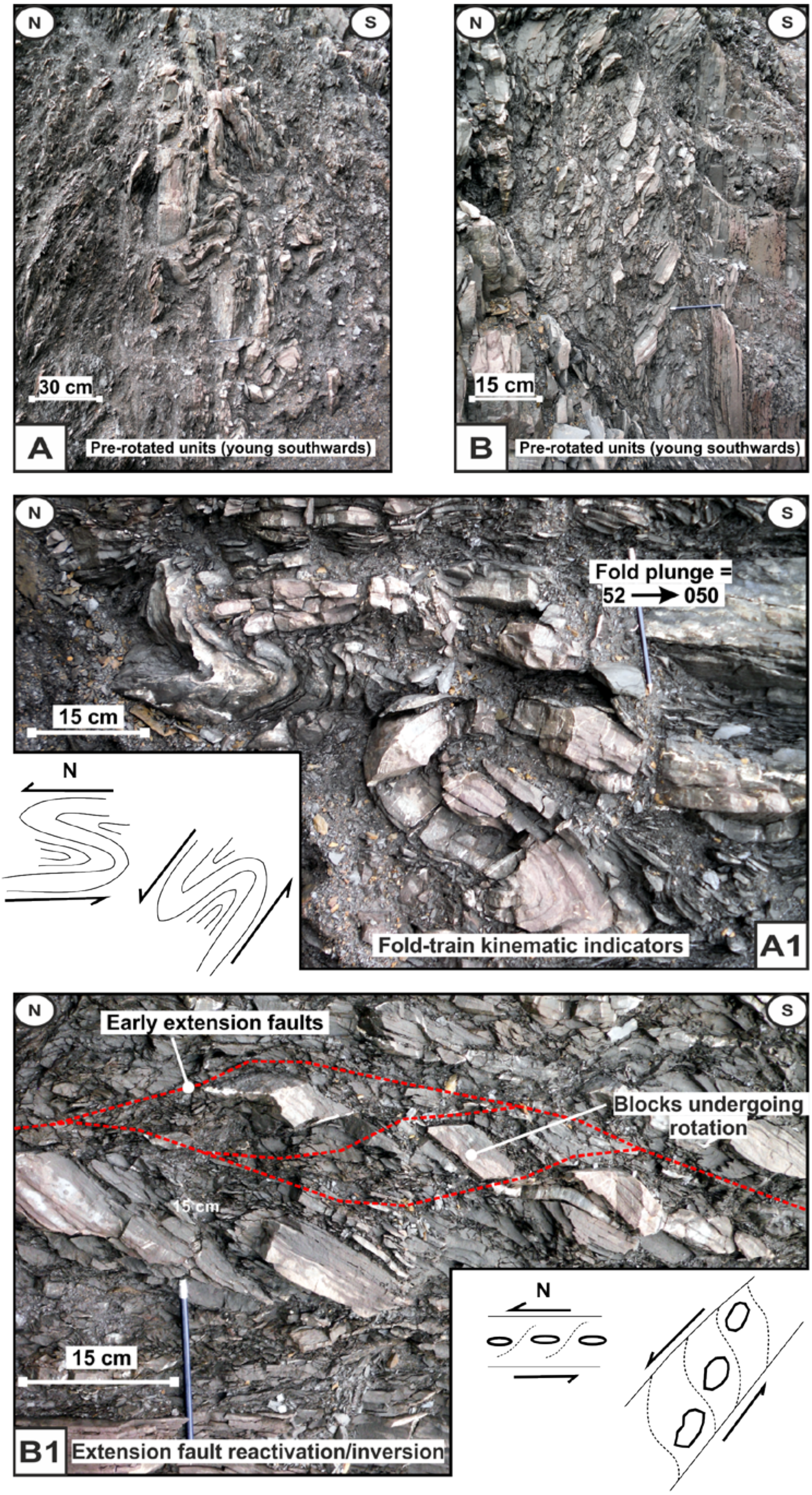


Figure 6.25: (A, B) Pre-rotation images of kinematic indicators within the San Emiliano siliciclastic sequence at Embalse de Caseras. Units are steeply inclined (80°) whilst younging to the south. **(A1, B1)** Once sequence is restored bedding-parallel deformation indicates a top-to-north transport.

Numerous reactivated extension faults are also identified within the Aralla region south of Embalse de Caseras (UTM 29N, 6945 7544), indicating a northwards transport along inverted extension faults within Silurian / Devonian strata (Figure 6.20b [6]; 6.26). Development of these syn-sedimentary extension faults within Silurian and Devonian strata on a regional-scale act as a pre-thrust weakness, assisting a transfer in displacement from the structurally lower Somiedo Sole Thrust to these higher units.

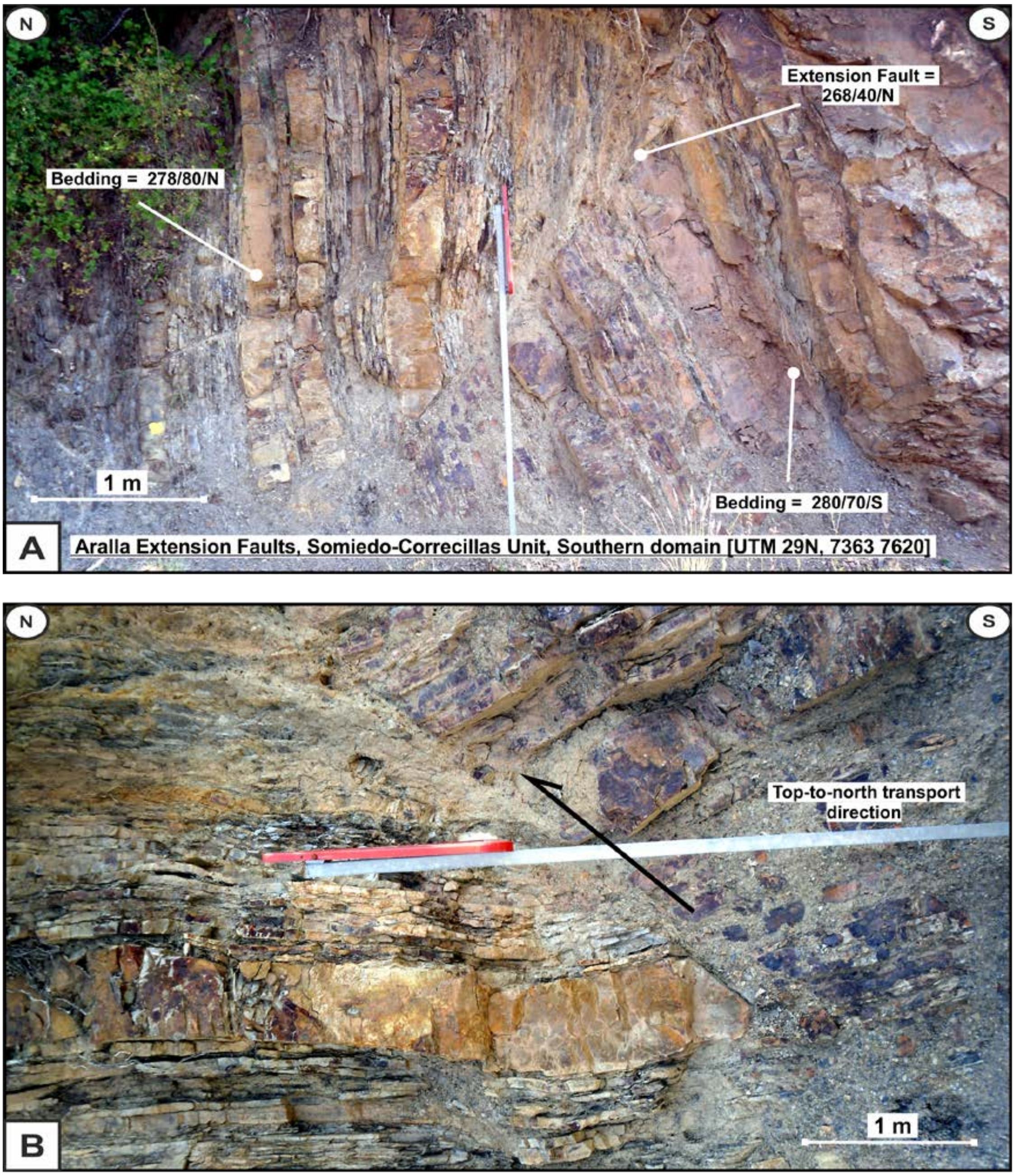
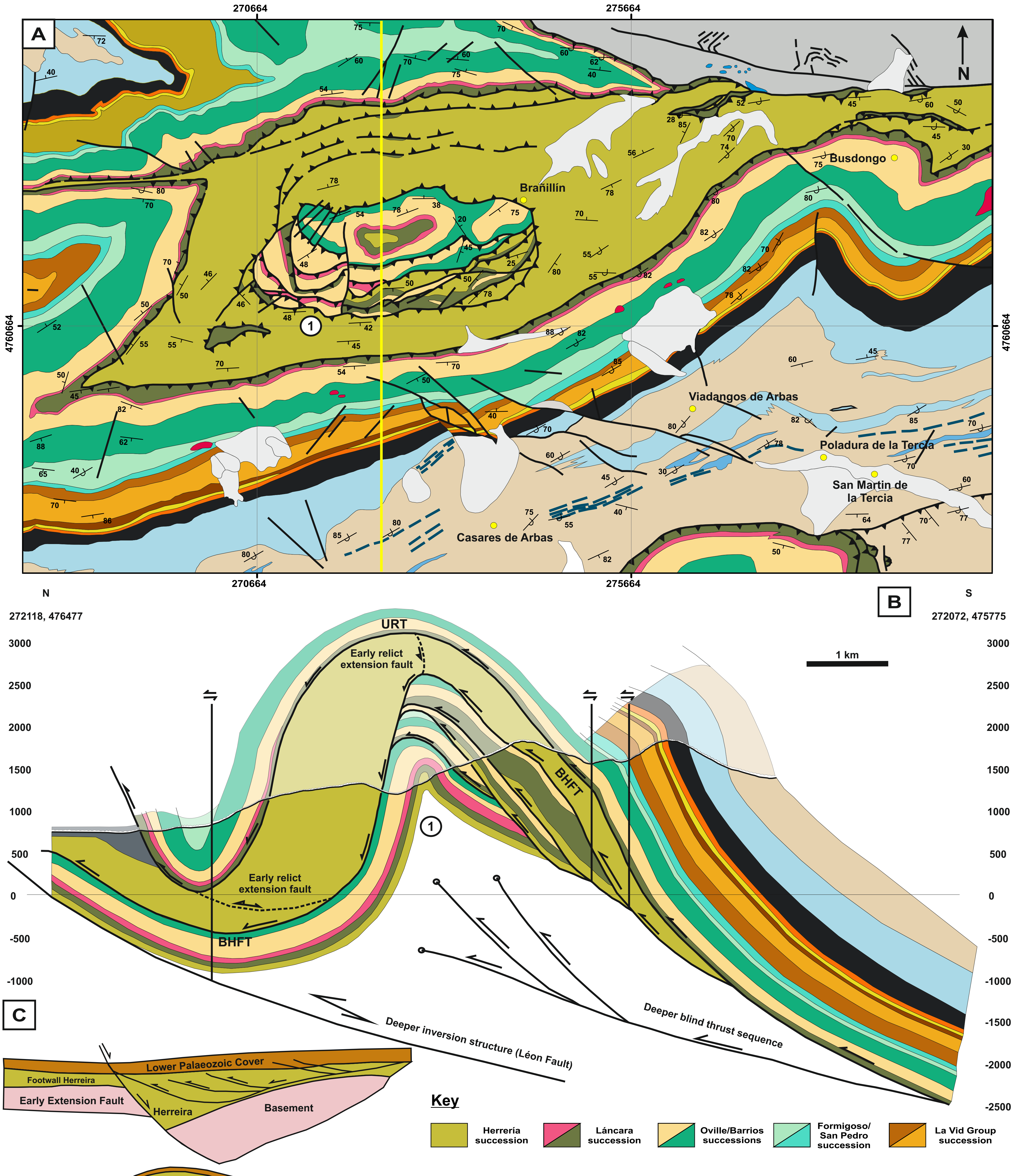


Figure 6.26: **(A)** Extension fault within the Silurian San Pedro Formation at Aralla. Sequence younging towards the south. **(B)** Extension fault rotated bedding-parallel highlighting kinematic translation/ inversion towards the north.

6.3.2.2. Cueto Negra-Brañillín Window: Bodon Unit

North of Embalse de Caseras, a major structure attributed to the location of the Luna Lineament by Nijman & Savage (1989) is identified within the Bodon Unit, south of the regionally dominant Léon Fault, the Cueto Negra-Brañillín Window (Figure 6.20a [16]; 6.27a). The Cueto Negra-Brañillín Window, (named after the eponymous hills and town / ski resort), depicts a predominant Herrería sequence (Figure 6.27b; 6.28a; 6.28b) comprising conglomerates, sandstones and silty limestones within which a second culmination comprising Lower Cambrian to Ordovician stratigraphy has developed (Figure 6.27a; 6.27b). Within the Cantabria-Asturian Arc, the Cueto Negra-Brañillín Window is an isolated feature, indicating that this structures development is linked to a favourable pre-thrust template and / or kinematic transport direction.

Exposure of the Herrería succession within the Cueto Negra-Brañillín Window is poor, especially on the northern-ward Asturian side of the Window. However, where outcrops are viewed, southward dipping (40 to 48°) strata is identified within the southern sections of the Window, whilst within the northern sections, much steeper units dipping northwards are identified (79 to 85°; Figure 6.28c). Within the Cueto Negra-Brañillín Window core, the second culmination comprising Láncara dolostones / limestones, Oville Formation siltstones and sandstones, and Barrios Formation quartzites, indicate considerable deformation along a series of hanging-wall and footwall ramps. Kinematic indicators within these units (e.g., hanging-wall anticlines / footwall synclines) highlight a top-to-north transport direction (Figure 6.28d). Further south within the internally deformed second window, evidence of large-scale folds indicating lateral (east-west) compression are observed along a series of hanging-wall and footwall ramps within fault network analyses (Figure 6.20b [7]; 6.29a; 6.29b).



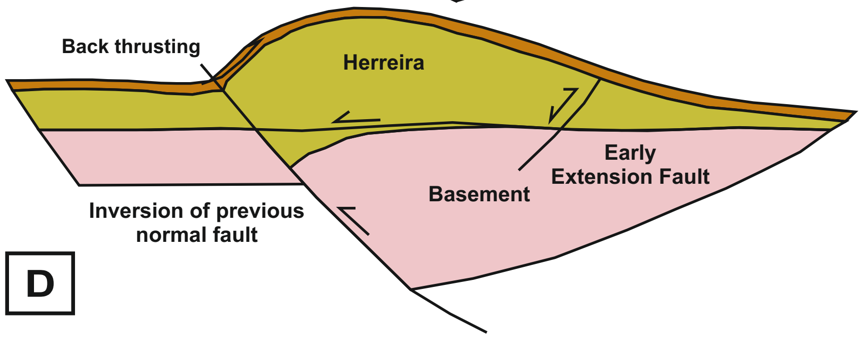


Figure 6.27: (A) Geological map of the Cueto Negra-Brañillín Window (Adapted after Alonso et al., 1991). Location of transport-parallel cross-section highlighted. Lithological units described within stratigraphical section (Figure 6.6). **(B)** Transport-parallel cross-section through the Cueto Negra-Brañillín Window. Cross-section highlights the interaction of early phases extension faults which have been inverted during north-south compression along a dominant frontal structure (i.e., the Léon Fault). This inverted Herrería-dominant sequence is then subsequently thrusted producing a second culmination within the core of the Cueto Negra-Brañillín Window. **(C, D)** Suggested development of the Cueto Negra-Brañillín Window from early extension along a half graben system to subsequent inversion along the Léon Fault.

Figure 6.28: **(A)** Overview of the Cueto Negra-Brañillín Window. Exposure of stratigraphical units is poor, apart from those identified during construction of the eponymous town / ski resort. **(B)** Herrería sequences comprising conglomerates, sandstones and silty limestones dominate the sequence. Although outcrop exposure of the Herrería is poor, within the northern Window units dip steeply towards the north **(C)**. Within the second Lower Cambrian to Ordovician culmination Window, Oville Formation siltstones / sandtones and Barrios quartzites highlight a top-to-north transport within deformed footwall and hanging-wall sequences **(D)**.

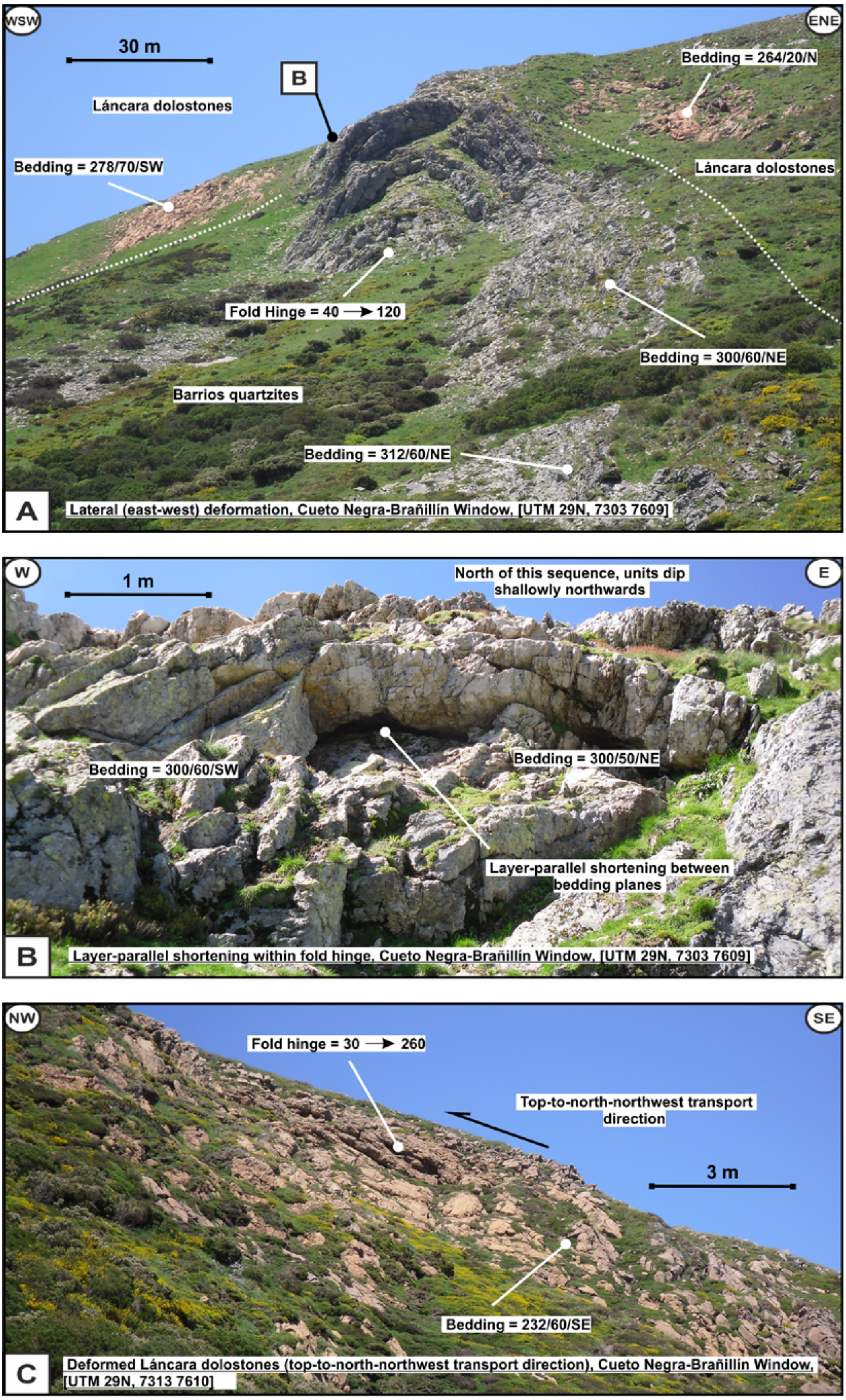


Figure 6.29: (A) Major fold hinge, identified within the central compartment of the second window interior, highlights lateral (east-west) shortening. Lateral shortening accommodated by layer-parallel shortening between individual bedding planes **(B)**. This shortening may be produced by localised compartmentalisation within the Window resulting in localised transpression along a north-south orientated fault during northwards thrust translation. **(C)** Folds within the Láncara dolostone highlight a top-to-north-northwest transport direction within the central sections of the Cueto Negra-Brañillín Window.

Large-scale folds within the Window interior, highlight top-to-north-northeast and top-to-north-northwest transport directions within different compartments along-strike (Figure 6.29a; 6.29c). Individual compartments are separated by a dominant north-south orientated fault along which localised transpression is observed (Figure 6.27a [1]; 6.29a). Development of these fold structures is accommodated by layer-parallel shortening between bedding planes (Figure 6.29b).

Cross-section analyses of the Cueto Negra-Brañillín Window indicate that this structure comprises a dominant frontal structure (i.e., an antiformal stack), which has been inverted over the present-day location of the Léon Fault (Figure 6.27b). Development of the Cueto Negra-Brañillín Window is suggested to have occurred within three phases. The first phase incorporates the development of a half graben during deposition of the Oville Formation within the Lower Cambrian (highlighted by differential thicknesses north to south within the Window; Figure 6.27c). Thrust propagation during a second phase scoops the Herrería off the basement, placing it on top of the cover Palaeozoic sequence during inversion tectonics. Relict extension faults are also transported within the northwards transport direction (Figure 6.27d). Further northwards propagation causes thrusts to truncate the core of the window, resulting in the development of a culmination comprising the previously covered Palaeozoic sequence, which domes the overlying Herrería sequence, producing the present day map-view (Figure 6.27a [1]; 6.27b [1]).

Observations within this research support those by Alonso *et al.*, (2009), which suggested that the Léon Fault is reactivated as a breaching thrust before lateral dextral strike-slip movements displace the Cueto Negra-Brañillín sequence by a minimum of one and a half kilometres (Figure 6.20a [17]). Exact timing of northwards propagation along these structures is unknown, but is suggested to be of either early Permian age during oroclinal bending or later reactivations during the Alpidic Orogeny.

6.3.2.3. Southern domain: Summary

Development of the Cueto Negra-Brañillín Window and kinematic indicators highlighted within the southern domain indicate a dominant northwards transport, as well as, providing further evidence highlighting the importance of inversion along pre-existing small- and large-scale frontal structures, such as the Léon Fault. Along-strike complexities are highlighted along the Somiedo Sole Thrust, particularly within the Villamanín / Rodiezmo region where large fault-propagation folds and evidence of buttressing is identified (i.e., Rodiezmo antiformal stack formation). Development of these structures indicates a potential transport-transverse structure (i.e., Villamanín Transverse Structure / Lateral Ramp). Hinterlandward alignments of thrust bifurcations along branch-lines and terminations of thrust faults along fault-tip points further support this interpretation. Thrust spacing increases hinterlandward, whilst a higher décollement is suggested for thrusts present within Devonian-dominant hinterland strata.

Development of these along-strike complexities within the Somiedo Sole Thrust, and the location of the Cueto Negra-Brañillín Window, led Nijman & Savage (1989) to suggest a large northeast-southwest orientated parental lineament for the development of these structures (i.e., the Luna Lineament). The existence of the Luna Lineament is addressed and placed in a regional, large-scale context within the discussion.

6.3.3. Somiedo-Correcillas Unit: Transition 'hinge' domain

The hinge domain (i.e., the 'Asturian Knee', Nijman & Savage, 1989), comprising the Barrios de Luna and the southernmost portions of the La Plaza geological map (Figure 6.30a; Marcos *et al*., 1980; Suárez *et al*., 1991) marks a distinct cross-strike transition from the fold-dominant northern domain into the fold-thrust dominant southern domain (Figure 6.10b). A series of cross-strike discontinuities are identified within the hinge domain, characterised by a dominant westwards concavity along the Somiedo Sole Thrust (Figure 6.30a [1]). Therefore, observations have been divided into the southern and northern hinge. Characteristics of the hinge core within the Bodon Unit are also identified. Stratigraphical separation diagrams (Figure 6.23; 6.24) established within the southern domain are continued into the southern hinge domain, whilst detailed transport-parallel and transport-lateral cross-section analyses are applied within the northern hinge across a distinct transport sub-parallel transverse structure, the Genestosa Fault. Along-strike complexities within the transition hinge domain have been previously attributed to the Aralla Lineament (Nijman & Savage, 1989).

6.3.3.1. <u>Transition 'hinge' domain: Southern hinge</u>

Within the easternmost zones of the southern hinge, a series of hanging-wall and footwall ramps are identified within fault network analyses from Los Barrios de Luna (UTM 29N, 6618 7479) forelandward to Láncara de Luna, where a bifurcation of the Somiedo Sole Thrust is observed (UTM 29N, 6144 7550; Figure 6.30a [2]; 6.30b [1, 2]). Hinterlandward thrusts also highlight a series of thrust bifurcations within this zone (Figure 6.30b [3]). Thrust ramps illustrate a series of undulating thrust faults developing along-strike with opposing thrust facing (Figure 6.30b [1]), indicating that thrusts are cutting up- and down-stratigraphically. Map-view patterns develop westwards from the La Pola de Gordon map into the Barrios de Luna map identifying two dominant fold sets within both domains

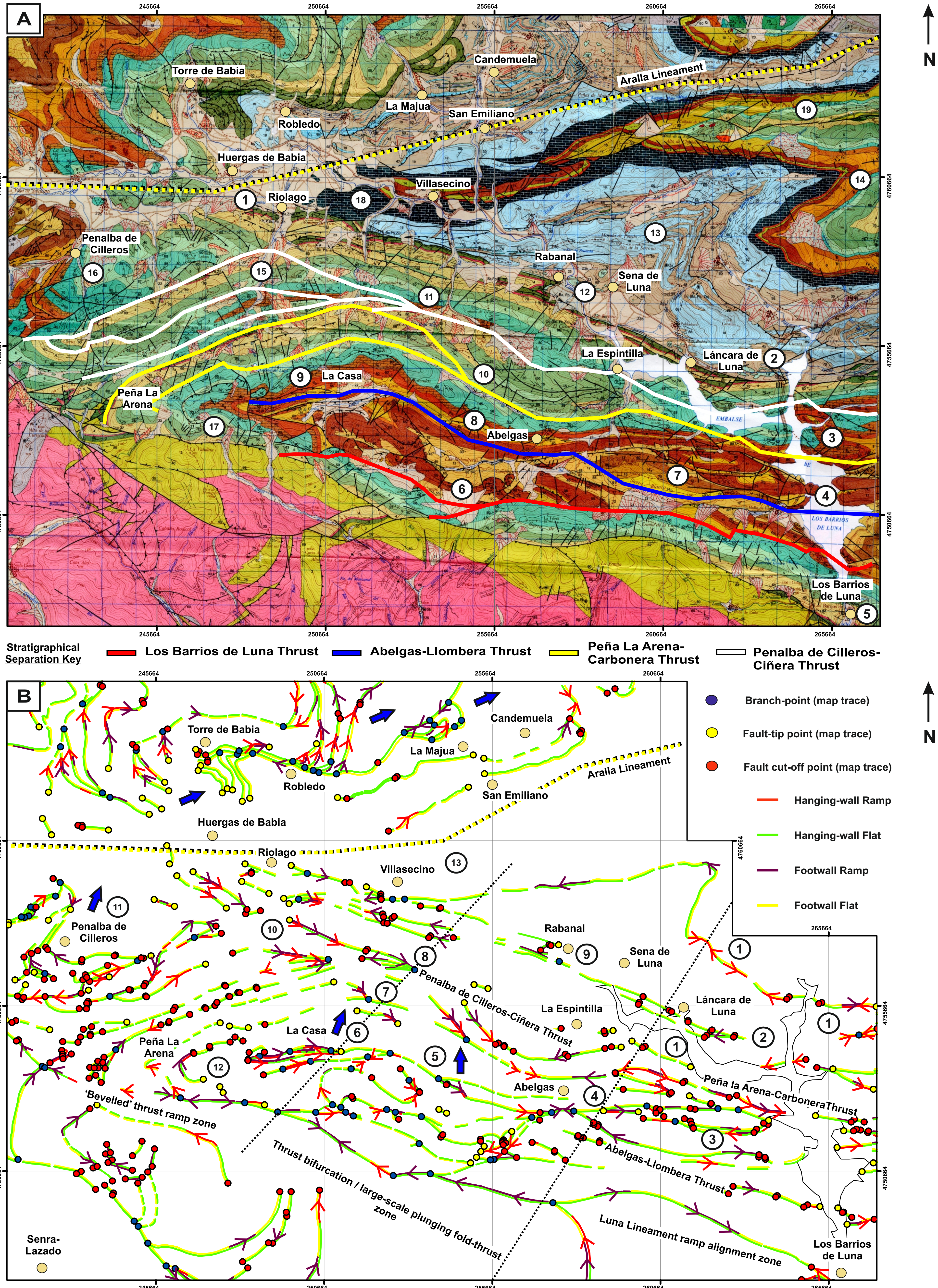


Figure 6.30: (A) Los Barrios de Luna geological map (Suárez *et al.*, 1991) highlighting distinct cross-strike architectural variations within map-view from the southern to northern hinge of the transition domain. Lithological descriptions and individual unit colours highlighted within map identified within stratigraphical section (Figure 6.6). Location of stratigraphical separation diagrams highlighted. **(B)** Fault network analysis of the Los Barrios de Luna southern hinge transition domain. Distinct alignments of thrust ramps, thrust bifurcations and fault tip-points within the southern hinge of the transition zone define a series of potential sub-decollement structures (i.e., Luna Lineament zone, Abelgas bifurcation zone and the 'bevelled' zone). Observations highlighted within the text are numbered, whilst transport kinematics are highlighted (blue arrows).

(Figure 6.20a; 6.30a). Hinterland folds are reactivated along their forelandward edges as thrusts, truncating the underlying fold series producing observed thrust ramps (Figure 6.30a [3, 4]). Observations are supported by stratigraphical separation diagrams which identify a series of breached folds along the eastern Embalse de Los Barrios de Luna shoreline placing younger stratigraphy onto older stratigraphy. Sequences rapidly develop into stratigraphically higher or lower units within the western shoreline (Figure 6.23b [2]; 6.24a [3]; 6.24b [2]). A potential transport-lateral structure could therefore be suggested within the present day location of the Embalse de Los Barrios de Luna.

Along-strike variations in thrust style are also observed across this potential transverse structure. Within the hinterland regions of this eastern zone, a distinct back thrust sequence is identified along the intersection of the Somiedo-Correcillas Unit and the southern arm of the structurally deeper Narcean Antiform Unit, comprising Herrería and Narcean Schist sequences at Los Barrios de Luna (UTM 29N, 6618 7479). This intersection aligns with the westward termination of a major fold sequence highlighted within the south-western edge of the La Pola de Gordon map; indicating that later thrust reactivations occur along the forelandward and hinterlandward edge of these folds producing ‘flower’ structures (Figure 6.20a [14]; 6.30a [5]). Further examples of localised back thrusts along the hinterland edges of folds are identified further westward along the Los Barrios de Luna Thrust (e.g., Peña Blanca; UTM 29N, 5304 7520; Figure 6.23a [1]; 6.30a [6]).

Westward development of thrusts into the Abelgas region highlight further thrust bifurcations along small ‘micro’ thrust sheets which are bound by north-south wrench faults, comprising folded sequences of Devonian strata ranging, from La Vid Group units to Santa Lucía, Huergas, Portilla and Nocedo lithologies (Figure 6.30a [7]; 6.30b [4]).

Thrusts develop along-strike westward into the Abelgas valley, west of the eponymous village, into a single dominant thrust plane (i.e., Abelgas-Llombera Thrust) which produces a Santa Lucía limestone-dominant ridge (i.e., the Las Melendreras ridge; Figure 6.30a [7, 8]). This Santa Lucía dominant ridge highlights several large-scale examples of east-west shortening along potential north-south (present day) orientated relict extension faults (Figure 6.30a [8]; 6.30b [5]; 6.31a).

Within the Abelgas valley, only a few thrust ramps are identified within fault network analyses where thrusts merge, bifurcate or truncate earlier folds (Figure 6.23b [3, 4]; 6.30b [5]). Along-strike within the Las Melendreras ridge, a large footwall ramp is identified where the Abelgas-Llombera Thrust cuts stratigraphically down from the Santa Lucía limestones into La Vid Group siltstones, highlighting a top-to-north transport direction (Figure 6.23b [3]; 6.31b). Further kinematic evidence supporting a top-to-north transport is identified within the La Vid Group along the valley floor within small hanging-wall anticlines (Figure 6.32).

Further west along-strike within the La Casa hillside (UTM 29N, 5006 7541), a plethora of hanging-wall and footwall ramps are identified within La Vid Group lithologies during fault network analyses, and stratigraphical separation diagram construction along the Abelgas-Llombera Thrust (Figure 6.23b [4]; 6.30a [9]; 6.30b [6]; 6.33a). Thrust ramps are identified cross-cutting relict extension faults within the La Vid Group sequence, indicating that a transecting north-south thrust direction truncates older, north-south aligned, pre-thrust extension faults (Figure 6.33b, 6.33c). It is therefore evident that more than one phase of thrusting is highlighted within the Abelgas valley, one which reactivates earlier north-south aligned extension faults, and a second later phase which transects these relict structures.

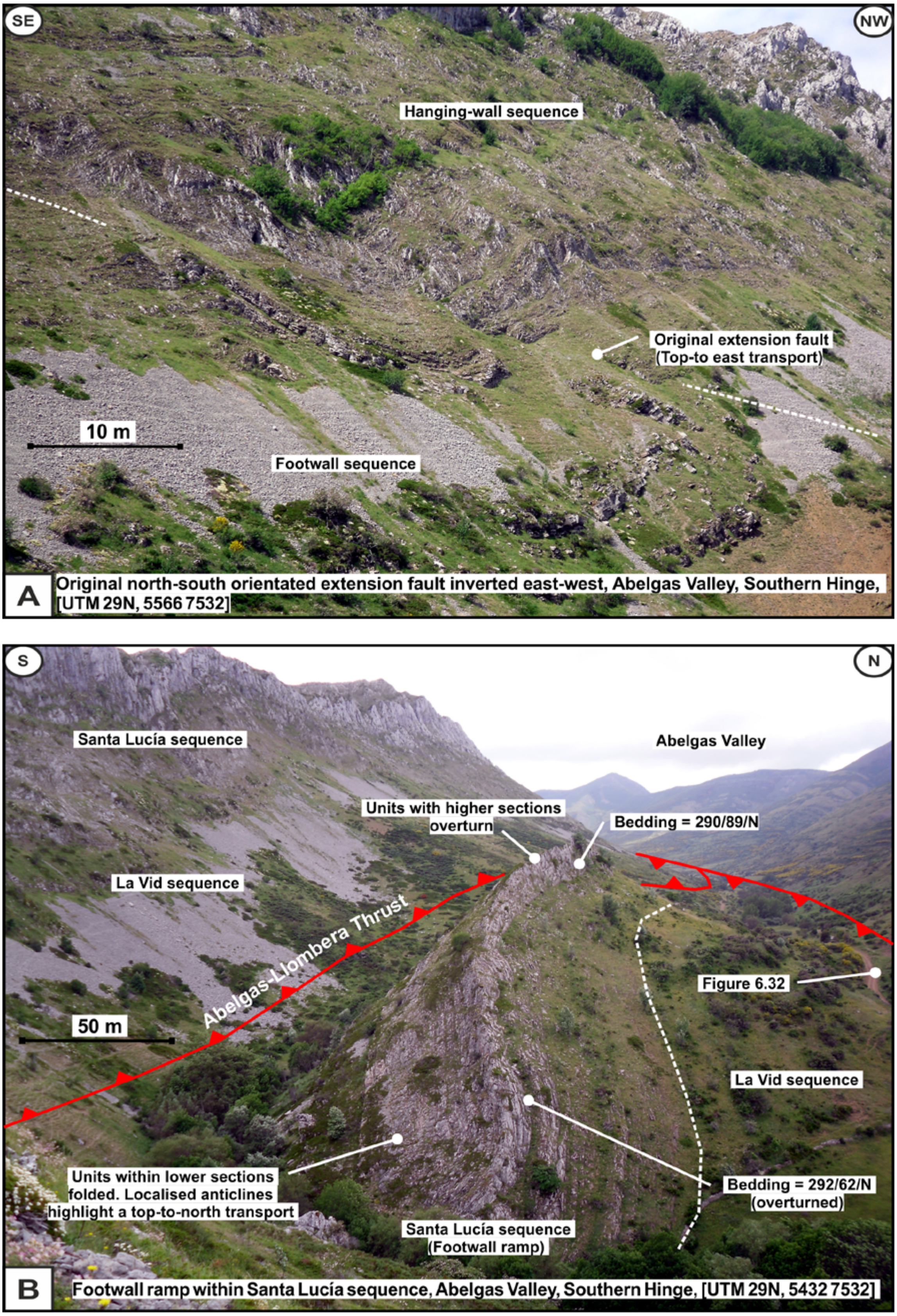
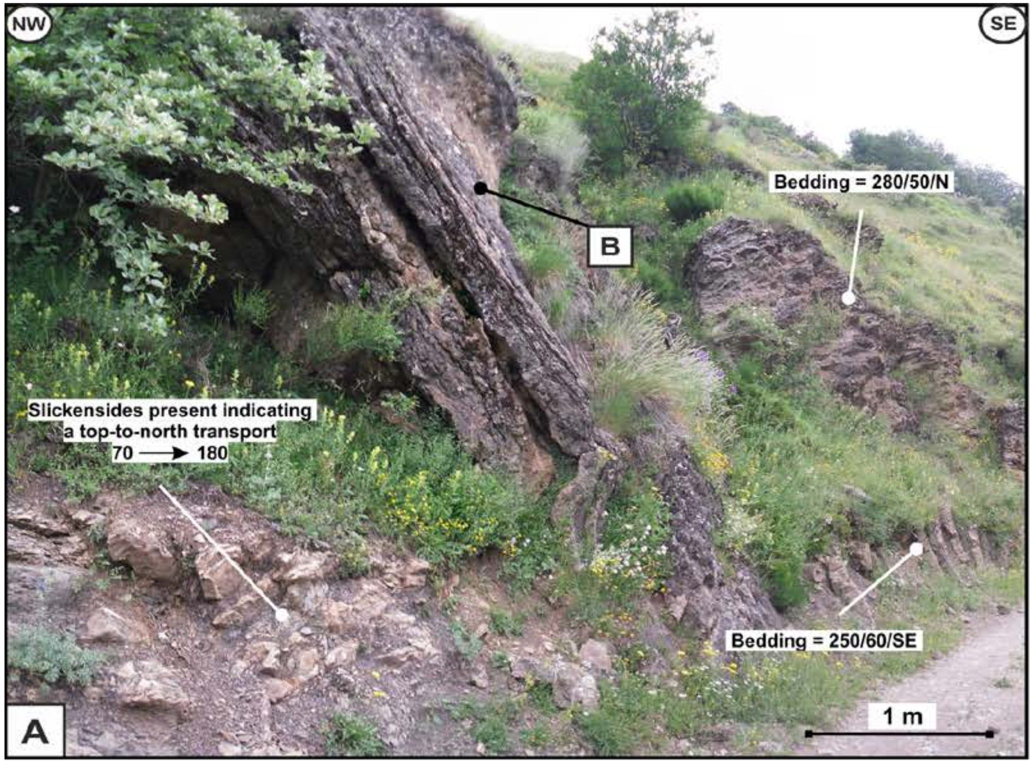
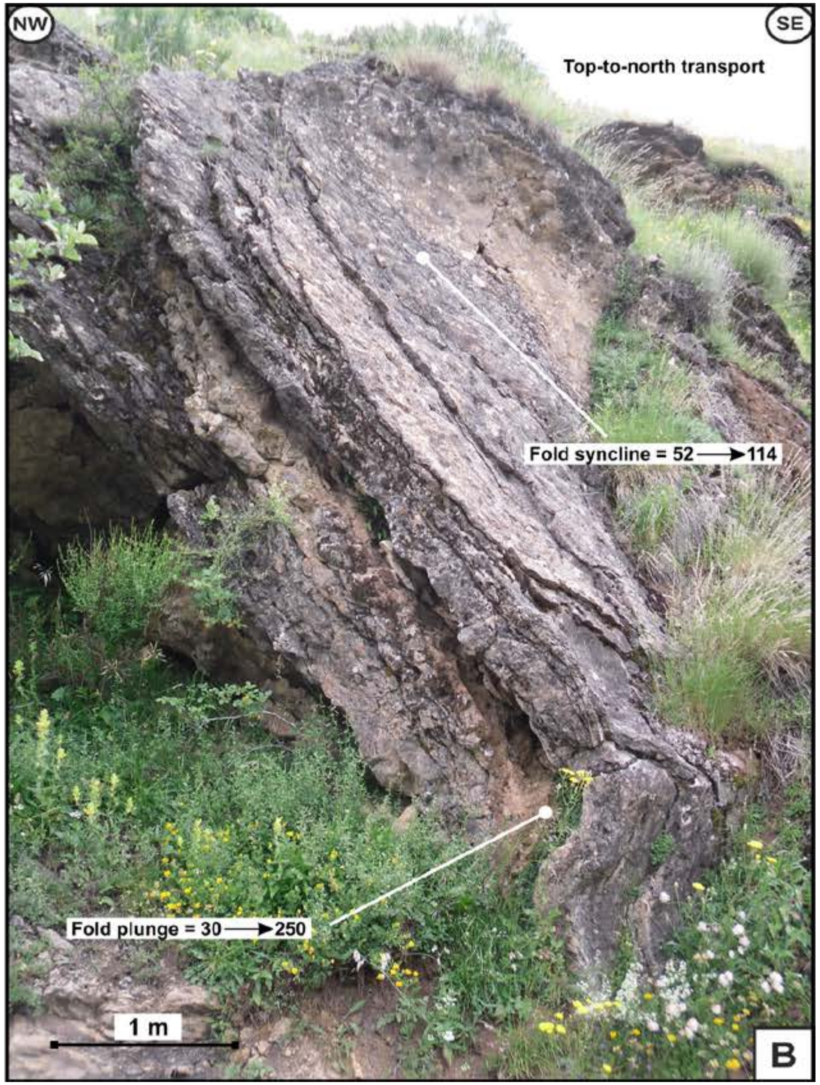


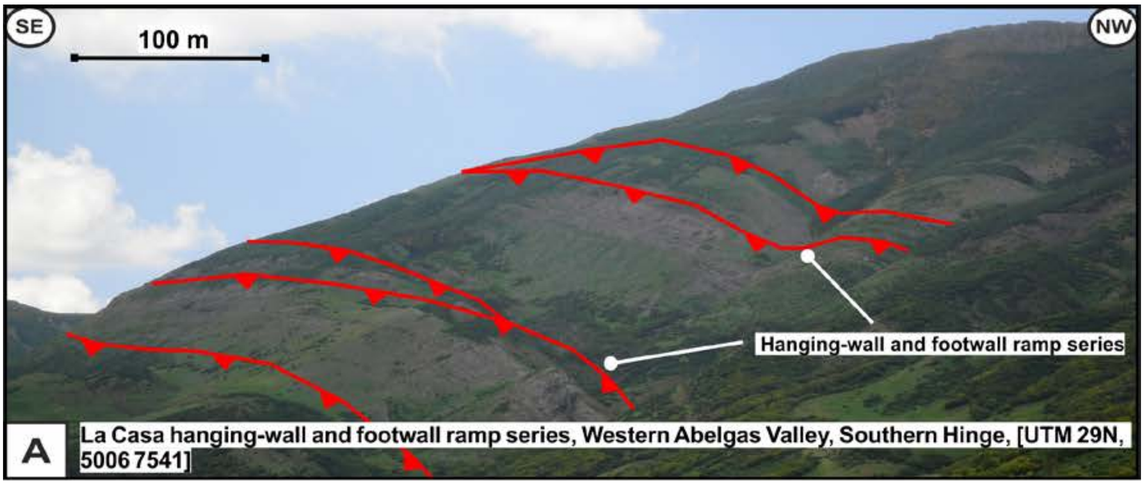
Figure 6.31: (A) Large-scale example of potential inversion along a relict north-south orientated (present day) extension fault within the Santa Lucía dominant southern ridge of the Abelgas valley. **(B)** Thrust ramp comprising Santa Lucía limestones identified within the footwall of the Abelgas-Llombera Thrust. Limestones are thrust over La Vid siltstones which dominate the valley floor sequences. A top-to-north transport is indicated during the development of this structure. Location of kinematic indicators highlighted (Figure 6.32).

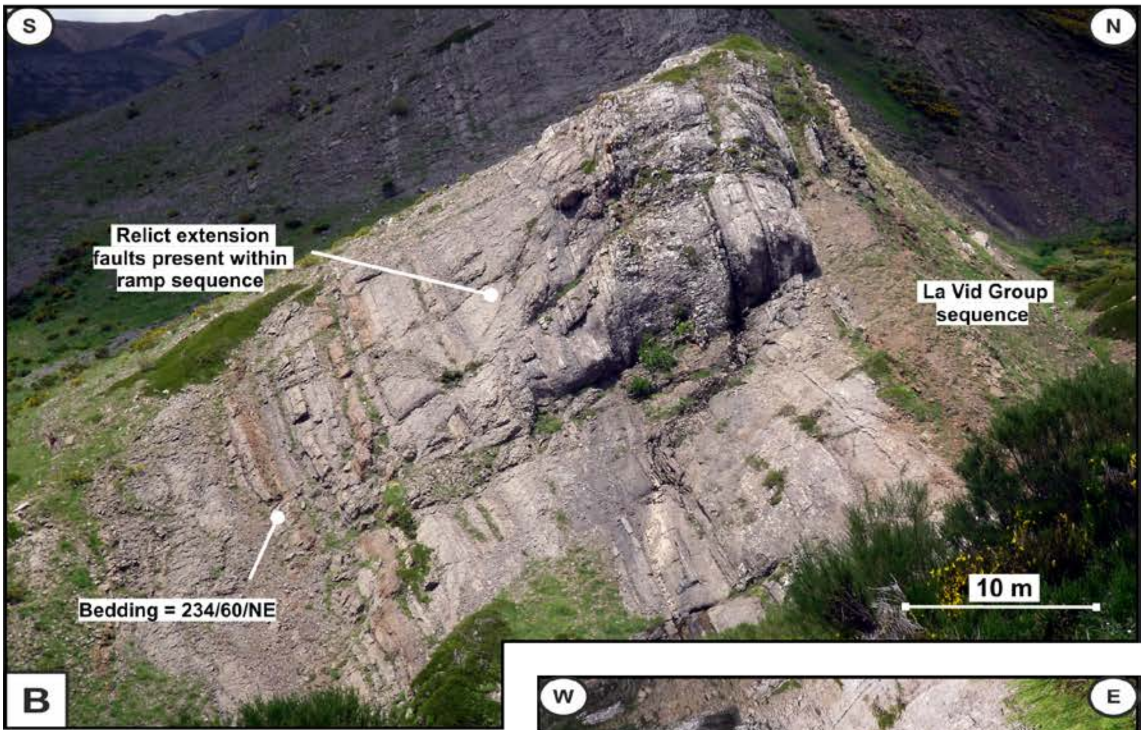




La Vid Group kinematic indicators, Abelgas Valley sequence, Southern 'Hinge' domain [UTM 29N, 5531 7534]

Figure 6.32: (A) Kinematic indicators within La Vid Group siltstones south of the Santa Lucía dominant footwall ramp sequence within the Abelgas valley. Slickenside evidence and the development of large hanging-wall anticlines **(B)** all indicate a top-to-north transport direction. Structures developed within the hanging-wall of a thrust within transects the Abelgas valley floor and merges laterally with the Abelgas-Llombera thrust further west up the valley.





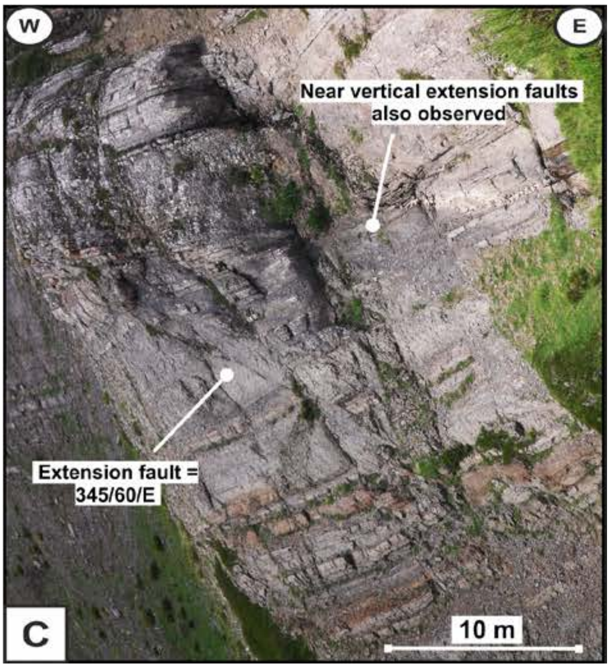


Figure 6.33: (A) La Casa hanging-wall/ footwall ramp series within La Vid Group silt/sandstones and dolostones/limestones. **(B)** Thrust ramp sequence highlighting truncated relict north-south orientated extension faults. When rotated bedding-parallel, sequence indicates original eastwards-dipping extension faults **(C, C1)**. Scales relative to ramp sequences.

Hanging-wall and footwall ramp series produced during thrust bifurcation within the La Casa hillside appear to be controlled by alternations between competent La Vid dolostones / limestones and intercalations of less competent mudstones and silt-/sandstones, as well as, relict extension faults which compartmentalise deformation. Eastward of the La Casa ramp series, along-strike thicknesses of relatively incompetent La Vid Group (Esla Member) shales increase eastward along a relict extension fault (Figure 6.34a [1]). Transpressional transport-lateral folds are identified above this thickened sequence, indicating that this major relict transport-orthogonal structure compartmentalised deformation along-strike, producing the observed La Casa ramp series westward of this structure, whilst transpressional and conical folds are produced eastwards against this structure (Figure 6.34b; 6.34c). Kinematic indicators (i.e., deformation fabrics within intercalated siltstone and mudstone units, production of conical folds, and hanging-wall anticlines) highlight transport directions ranging from top-to-north, to north-northwest, supporting observations of localised transpression against pre-existing extension structures (Figure 6.34d).

Bifurcations along the La Casa ramp series within the Abelgas valley (Figure 6.30a [9]; 6.30b [6]) are aligned northeast-southwest with further forelandward bifurcations of the Peña La Arena-Carbonera Thrust (Figure 6.24a [4]; 6.30a [10[; 6.30b [7]), Penalba de Cilleros-Ciñera Thrust (Figure 6.24b [3]; 6.30a [11]; 6.30b [8]), together with, the Somiedo Sole Thrust south of Rabanal (UTM 29N, 5734 7573; Figure 6.30a [12]; 6.30b [9]). Within the Bodon Unit north of Rabanal a large-scale, northeast-plunging, folded thrust within Valdeteja limestone and San Emiliano siliciclastic lithologies is identified (Figure 6.30a [13]). This plunging folded thrust also aligns with folds developed west of the Cueto Negra-Brañillín Window (Figure 6.30a [14]).

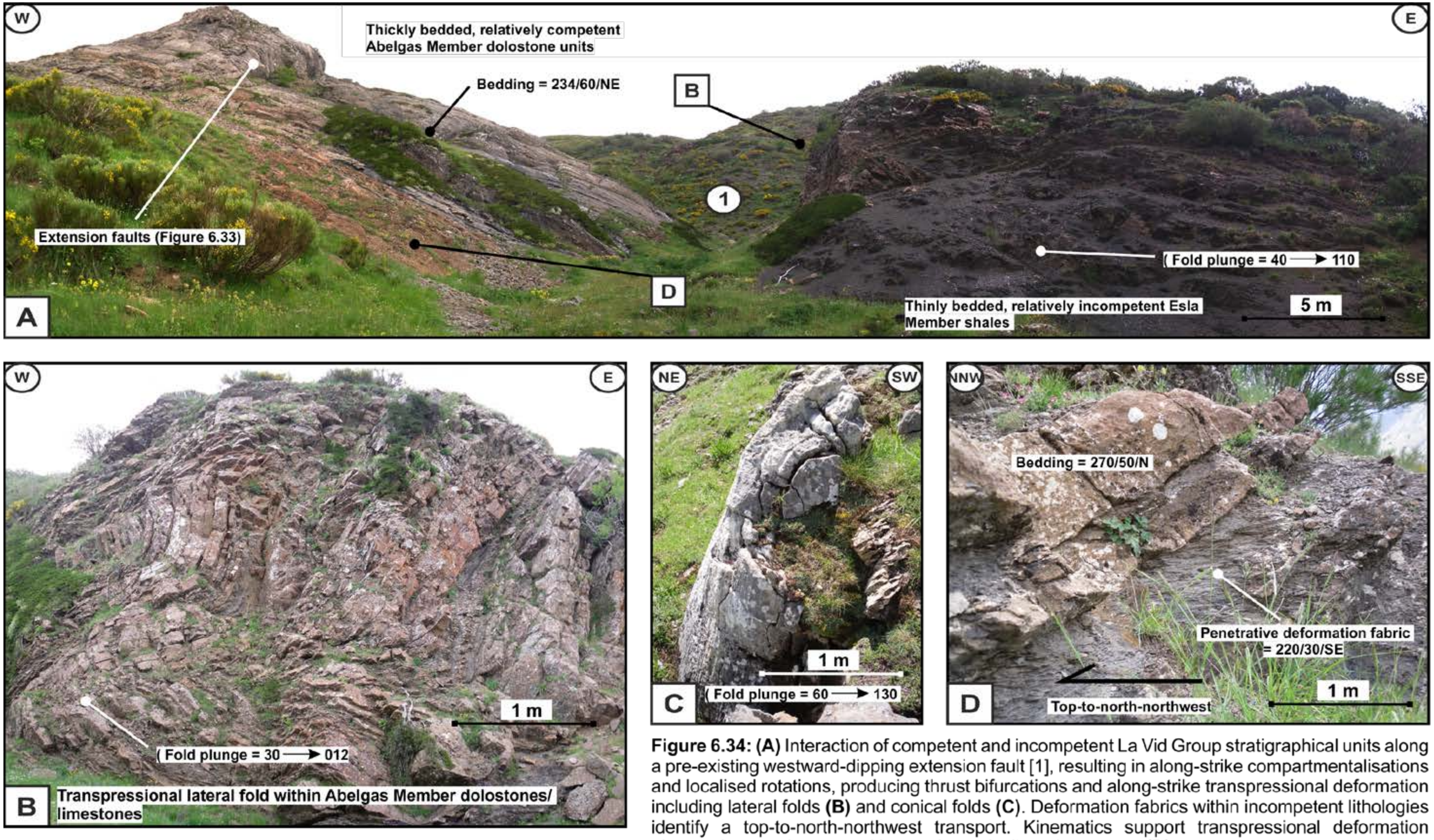


Figure 6.34: (A) Interaction of competent and incompetent La Vid Group stratigraphical units along a pre-existing westward-dipping extension fault [1], resulting in along-strike compartmentalisations and localised rotations, producing thrust bifurcations and along-strike transpressional deformation including lateral folds **(B)** and conical folds **(C)**. Deformation fabrics within incompetent lithologies identify a top-to-north-northwest transport. Kinematics support transpressional deformation observations against pre-exiting north-south aligned structures **(D)**.

Eastwards of this bifurcation zone, the Peña La Arena-Carbonera and Penalba de Cilleros-Ciñera thrusts develop into a distinct 'bevelled zone' (Nijman & Savage, 1989), stretching southwest from Riolago (UTM 29N, 4937 7598; Figure 6.30a [15]; 6.30b [10]) to south of Penalba de Cilleros (UTM 29N, 4321 7584; Figure 6.30a [16]; 6.30b [11]). Stratigraphical separation diagrams and map-pattern observations along these thrusts indicate that this 'bevelled zone' comprises a series of thrusts which breach pre-existing folds and truncate forelandward thrusts which develop southwards from the northern hinge, aligned 90° to the bevelled zone (Figure 6.24a [5]; 6.24b [4]; 6.30a [15]; 6.30b [10]). These observations are indicative of an out-of-sequence thrust development. Hinterland thrusts west of Abelgas also indicate that hinterlandward thrusting continues into deeper thrust sheets which bring up Herrería and Narcean schist units, producing folded thrusts within forelandward thrust sheets (UTM 29N, 4632 7534;Figure 6.30a [17]; 6.30b [12]).

South of Riolago, mineralisation is identified within Barrios quartzites along thrust bifurcations of the forelandmost Penalba de Cilleros-Ciñera Thrust, indicating that hydrothermal iron-rich fluids perforate the thrust front (Figure 6.35). Deformation structures within the Riolago valley between thrusts within the 'bevelled zone' highlight a series of broad folds aligned north-south indicating east-west compression (Figure 6.36a; 6.36b). These 'fold swarms' radiate outwards mirroring the westward concavity of the transition 'hinge' domain, suggesting that these structures were produced during east-west compression and subsequently rotated during oroclinal bending of the hinge domain (Figure 6.36c). Northwest of the 'bevelled zone', large scale fold-thrust structures within the La Vid Group sequence above Penalba de Cilleros (UTM 29N, 4321 7584; Figure 6.30a [16]; 6.30b [11]) identify a top-to-northeast transport direction, whilst further highlighting evidence of out-of-sequence thrusting (i.e., truncation of underlying thrusts and folds; Figure 6.36d). An along-strike change from a north (010°) to north-east transport direction (030°) is therefore indicated.

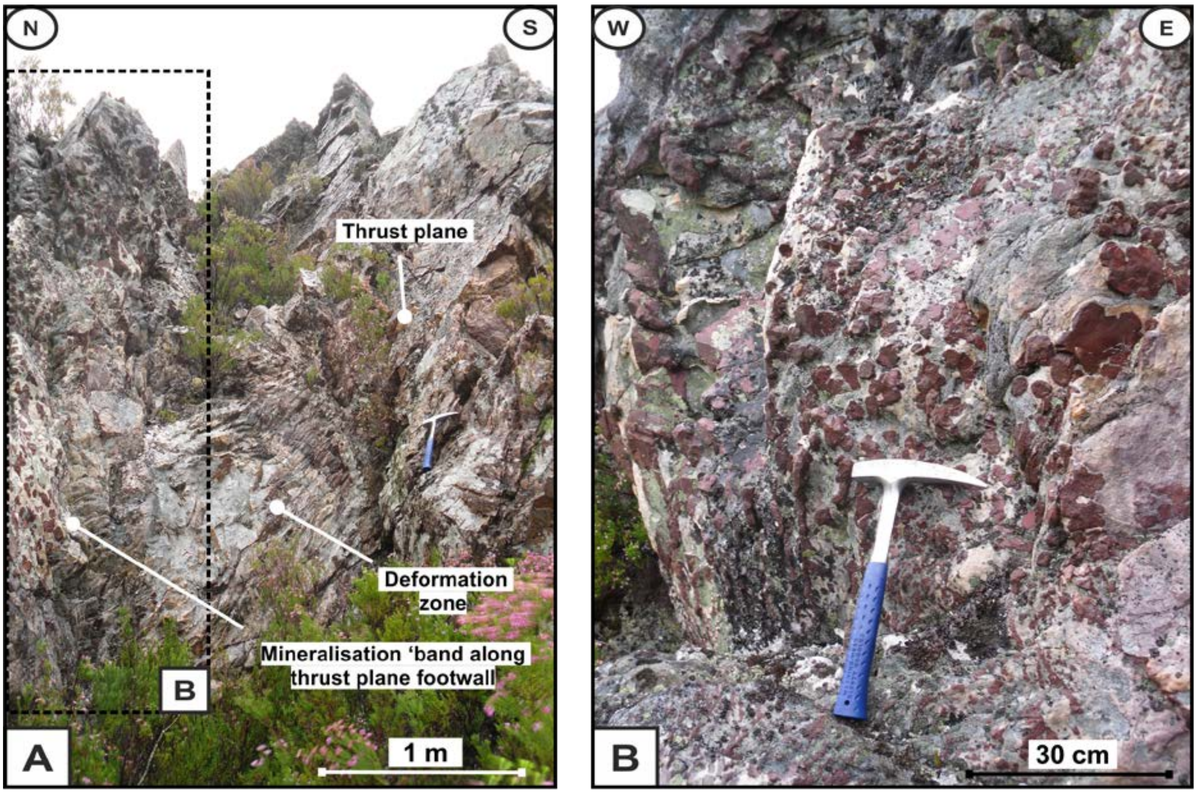


Figure 6.35: (A) Mineralisation along the forelandmost Penalba de Cilleros-Ciñera Thrust within Barrios quartzites, which transects lithologies transverse to stratigraphical strike. **(B)** Close up view of mineralisation within the footwall of the Penalba de Cilleros-Ciñera Thrust. Individual 'nodules' range in size from a few millimetres to a maximum of 10 cms.

Development of the 'bevelled zone' along a series of aligned thrust bifurcations and the production of large northeast-plunging folds and folded thrusts suggests that a potential transport-oblique (i.e., northeast-southwest orientated) sub-décollement structure may be present (Figure 6.30b [6, 7, 8, 9]). The development of this transport-oblique structure is most likely the result of oroclinal bending during the Early Permian forming the fold swarms identified within the southern Riolago valley. However, truncations of forelandward structures north of the 'bevelled zone', indicate that a phase of reactivation must also have occurred along this thrust front, truncating underlying thrust sheets. This out-of-sequence development most likely occurred during the tightening of the Cantabria-Asturian arc during north-south compression within the early Permian Period or during later Alpidic deformation events. Fluid flow, resulting in mineralisation within the bevelled zone, could have occurred during any phase of deformation; however, evidence suggests

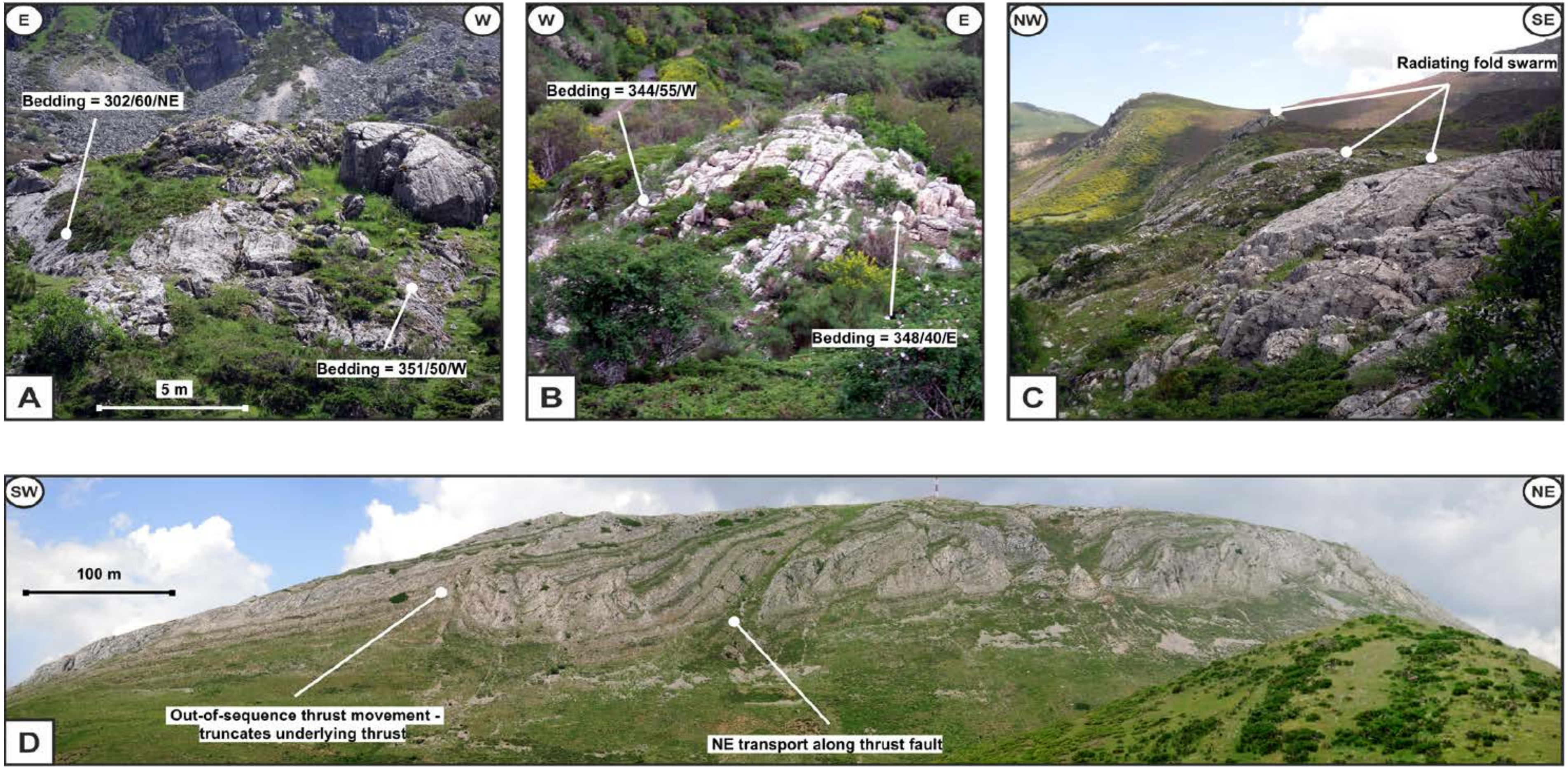


Figure 6.36: (A, B) Examples of broad folds highlighting east-west compression. These 'fold swarms' radiate outwards from a northeast-southwest alignment to northwest-southeast, mirroring bending within the hinge zone **(C)**. Above the town of Penalba de Cilleros (UTM 29N, 4321 7584), large-scale folds and truncating thrusts (highlighting out-of sequence movements), identify a north-east transport direction **(D)**.

that this occurred during the secondary breaching or reactivation phase along the forelandmost Penalba de Cilleros-Ciñera Thrust, due to its localisation along the thrust front and the thrusts transversal orientation to stratigraphical strike. Numerous examples of mineralisation and mineral extraction are identified within map-view along the Somiedo Thrust. However, a dense cluster of these are located within the southern hinge domain indicating a zone of increased fluid migration. Mineral deposits include barite, copper, lead and zinc.

6.3.3.2. <u>Transition 'hinge' domain: Central core</u>

The core of the transition hinge domain (Figure 6.30a [18]), comprising the Bodon Unit, is dominated by a large (1.5 kilometre wide, 18 kilometres long), east-northeast-west-southwest orientated antiformal fold, comprising Devonian to Carboniferous age lithologies (i.e., Santa Lucia to Barcaliente formation limestones). Within map-view, this antiformal fold continues east-north-eastwards, joining the Léon Fault north of the Cueto Negra-Brañillín Window (Figure 6.30a [19]). The antiformal fold is transected by two sets of wrench faults orientated northeast-southwest and northwest-southeast.

West of the village of Villasecino (UTM 29N, 5384 7600), wrench faults of both sets are identified transecting Santa Lucía Formation limestones to Ermita and Balaes formation sandstones and grainstones (Figure 6.37). A dominant northwest-southeast wrench fault plane is identified which truncates a series of smaller scale north-northeast-south-southwest orientated wrench fault planes (Figure 6.37a). Both wrench fault sets highlight sinistral movements which compartmentalise earlier produced geometrical and kinematic transport indicators. Significant alterations of the wrench plane surfaces by later fluids are also observed (i.e., flowstone production; Figure 6.37b; 6.37c; 6.37d).

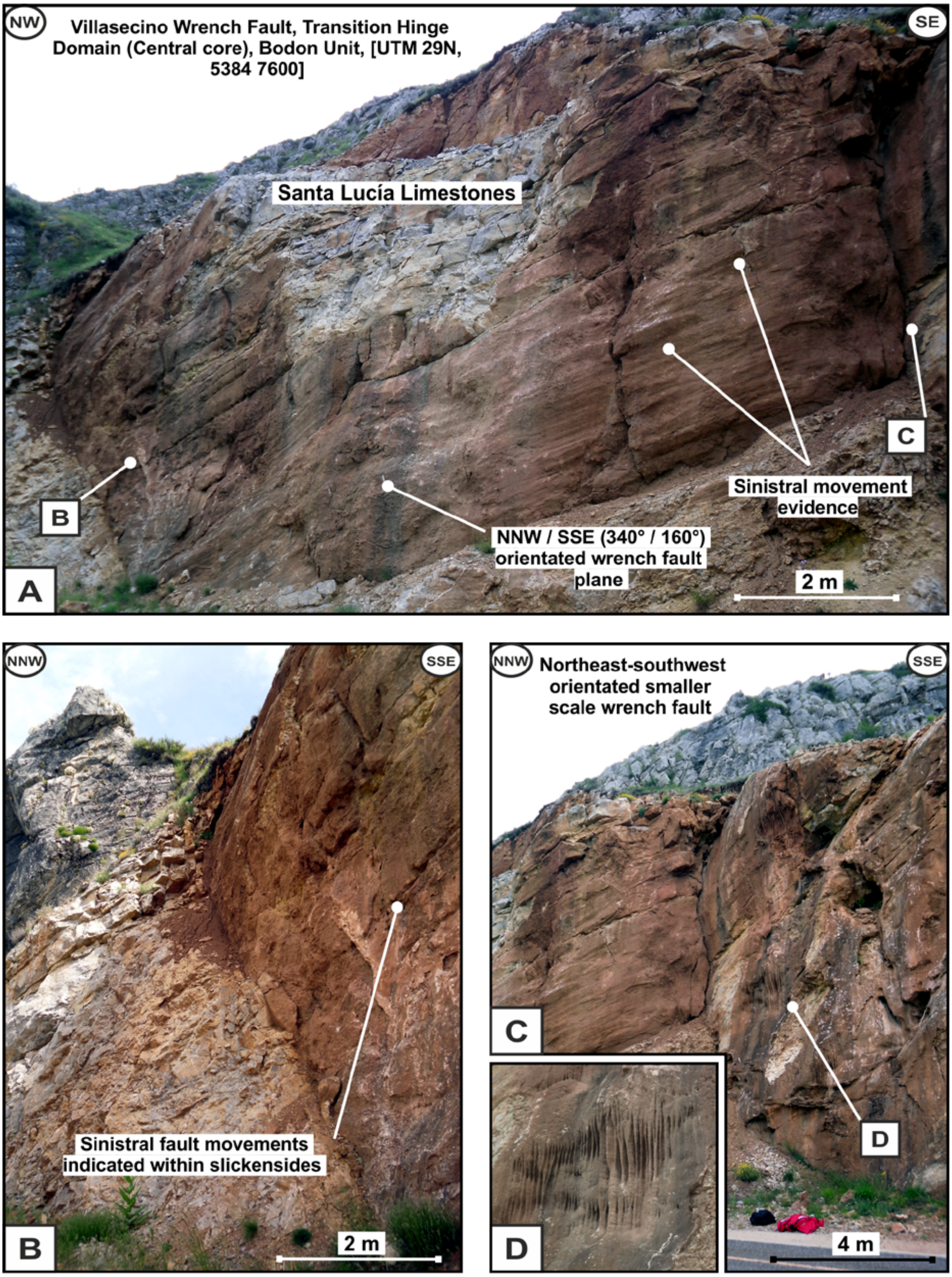


Figure 6.37: **(A)** Two sets of wrench faults are identified west of the village of Villasecino, a dominant northwest-southeast orientated plane, and a series of smaller scale wrench faults orientated north-northeast-south-southwest which truncate this original dominant plane (**B, C**).Both wrench fault sets highlight a dominant sinistral movement. **(D)** Significant later fluid flow alteration is also observed (i.e., flowstone) along the wrench fault planes.

Within the core of the northern limb, one of the northwest-southeast orientated wrench faults is observed entraining younger red nodular siltstones and limestone stratigraphical successions (i.e., Ermita / Balaes to Alba Formation units; Figure 6.38a; 6.38b). Soft sediment deformation is identified above this entrained succession mixing younger stratigraphical successions with older Santa Lucía limestones (Figure 6.38c). Intrusions (i.e., neptunian dykes) of these younger stratigraphical successions are also observed (Figure 6.38d).

A series of small thrust faults are observed within Santa Lucía Formation limestones highlighting a top-to-south transport direction which are offset and compartmentalised by the wrench faults (Figure 6.39a). However, a series of thrusts are also observed truncating the wrench faults entraining younger stratigraphical successions identified within the neptunian dykes (Figure 6.39b). Conversely, within the southern limb of the antiformal fold, a series of broad, east-west orientated, folds are identified which are truncated by a series of small-scale thrust faults and neptunian dykes (Figure 6.39c). Deformation fabrics within finer-grained siltstone layers indicate a top-to-north-northeast transport direction for these thrusts (Figure 6.39d). These structures are truncated by a later thrusting phase highlighting a top-to-south transport (Figure 6.39c).

The central core of the transition hinge domain is therefore dominated by a series of large- and small-scale structures which highlight a distinct structural and kinematic evolution. A large east-northeast-west-southwest orientated antiformal fold is observed, a structure which has been identified as a large conical fold within Pastor-Galán *et al*., (2012) (Figure 6.30a [18, 19]). This conical fold is truncated by two sets of wrench faults which compartmentalise internal deformation of the fold, whilst entraining younger stratigraphical units. Younger stratigraphical units are also intruded by a series of small neptunian dykes

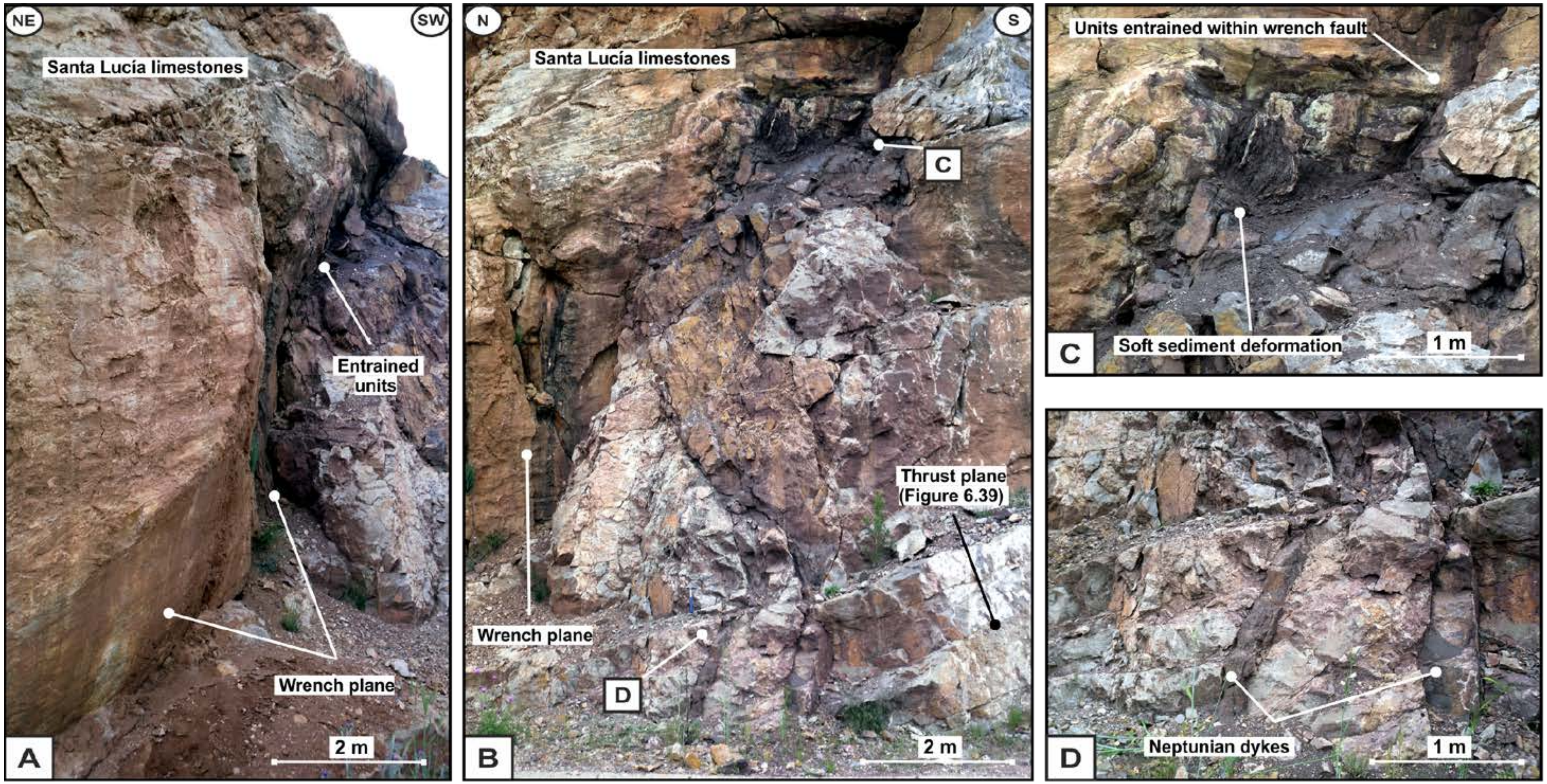
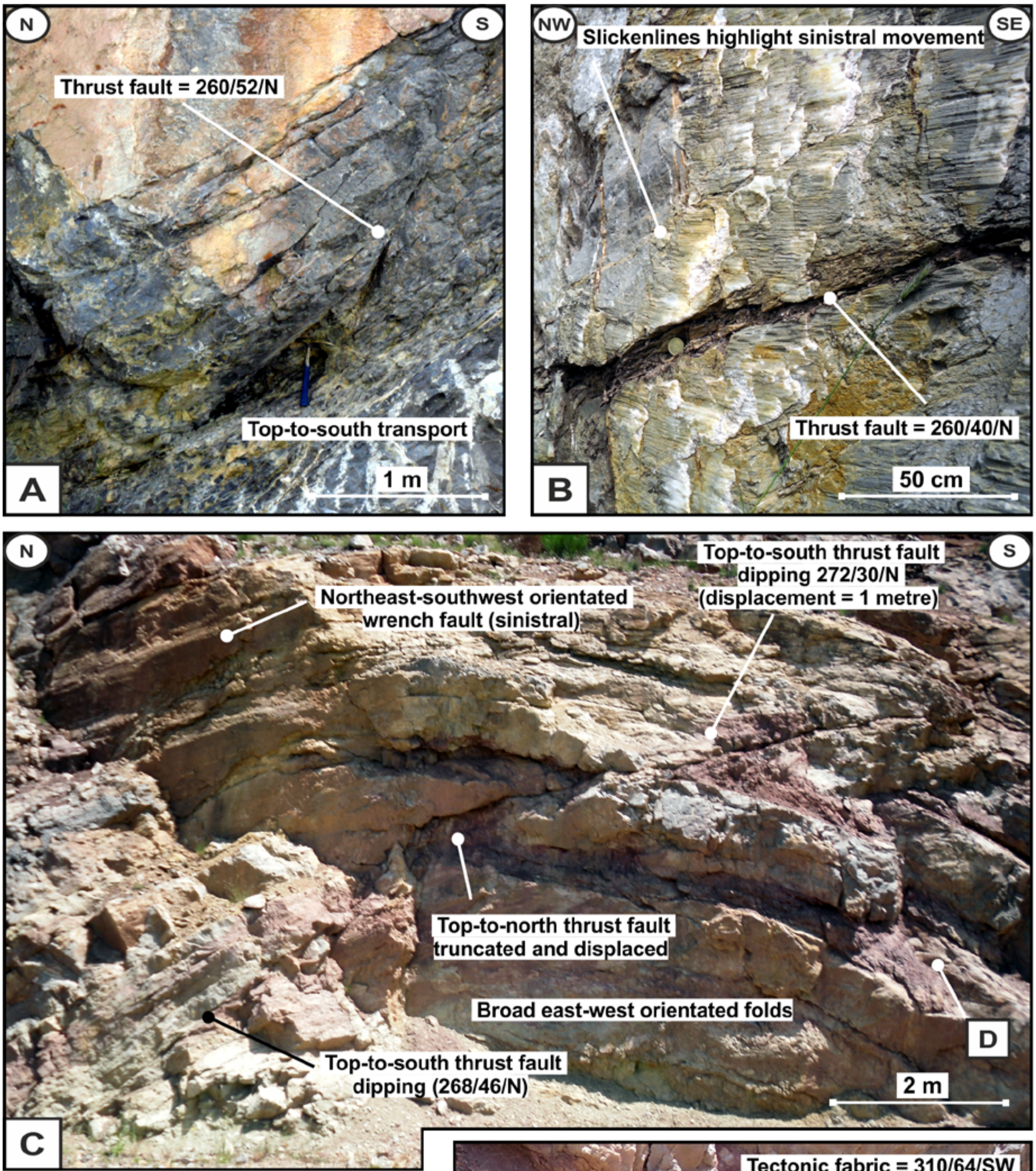


Figure 6.38: (A, B) Northwest-southeast orientated wrench plane along which younger stratigraphical units (i,e., Ermita / Balaes and Alba Formation siltstones) are entrained. Location of thrust entraining younger material also identified. **(C)** Soft sediment deformation is highlighted within the higher regions of the wrench fault. This suggests that a phase of wrench faulting occurred pre-lithofication. **(D)** Younger stratigraphical units are also intruded as small neptunian dykes within the Santa Lucía Formation limestones further supporting soft-sediment deformation.



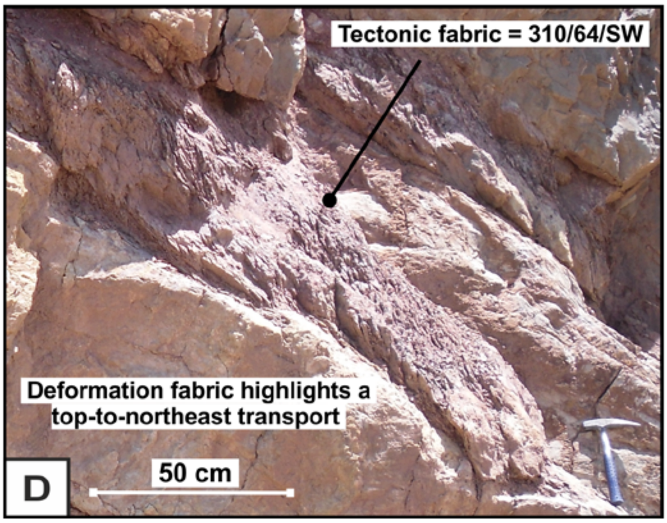


Figure 6.39: (A) Small thrusts within the northern limb of the antiformal fold are compartmentalised highlighting a top-to-south transport direction. **(B)** Further thrusts highlighting a top-to-south transport truncate these wrench faults, indicating more than one phase of thrusting. **(C)** Within the southern fold limb, broad folds orientated east-west are produced which are truncated by northwards propagating thrusts. Fine grained siltstones highlight a north to north-northeast transport **(D)**. Northwards propagating thrusts are subsequently truncated by a later set of southward propagating thrusts **(C)**.

resulting in soft-sediment deformation structures during lithification. It is therefore evident that an early phase of northwest-southeast orientated wrenching must have occurred pre-, to syn-lithification to have resulted in the development and entrainment of these structures. Development of early phase wrench faulting also assists the compartmentalisation of thrust development and propagation.

Within the southern limb of the antiformal fold, broad, east-west orientated folds are produced during north-south compression. These folds are truncated during northwards thrust propagation. A second phase of thrusting (i.e., top-to-south transport) subsequently truncates the wrench faults, the east-west orientated folds and the northwards-propagating thrusts. A final phase of wrenching, producing the dominant northwest-southeast orientated wrench fault plane then truncates all of these structures.

6.3.3.3. Transition 'hinge' domain: Northern hinge

The northern hinge of the transition domain, comprising the northern sections of the Barrios de Luna geological map and the southernmost portions of the La Plaza geological map (Suárez *et al*., 1991 and Marcos *et al*., 1980, respectively), is dominated by map patterns highlighting a cross-strike structural style change across an east-northeast to west-northwest orientated, ten kilometre long, transverse fault termed here the Genestosa Fault (Figure 6.40a [1]; 6. 40b [1]). Within the southern wall of the Genestosa Fault, map patterns detail the development of several structural discontinuities along the Somiedo-Correcillas Sole Thrust and along structurally higher thrusts within the La Vid Group succession including the Torre de Babia antiformal stack (Figure 6.40a [2]), the Robledo-Cospedal splay series (Figure 6.40a [3]), and the La Majúa duplex (Figure 6.40a [4]). Conversely, within the northern wall of the Genestosa Fault, large-scale folds are

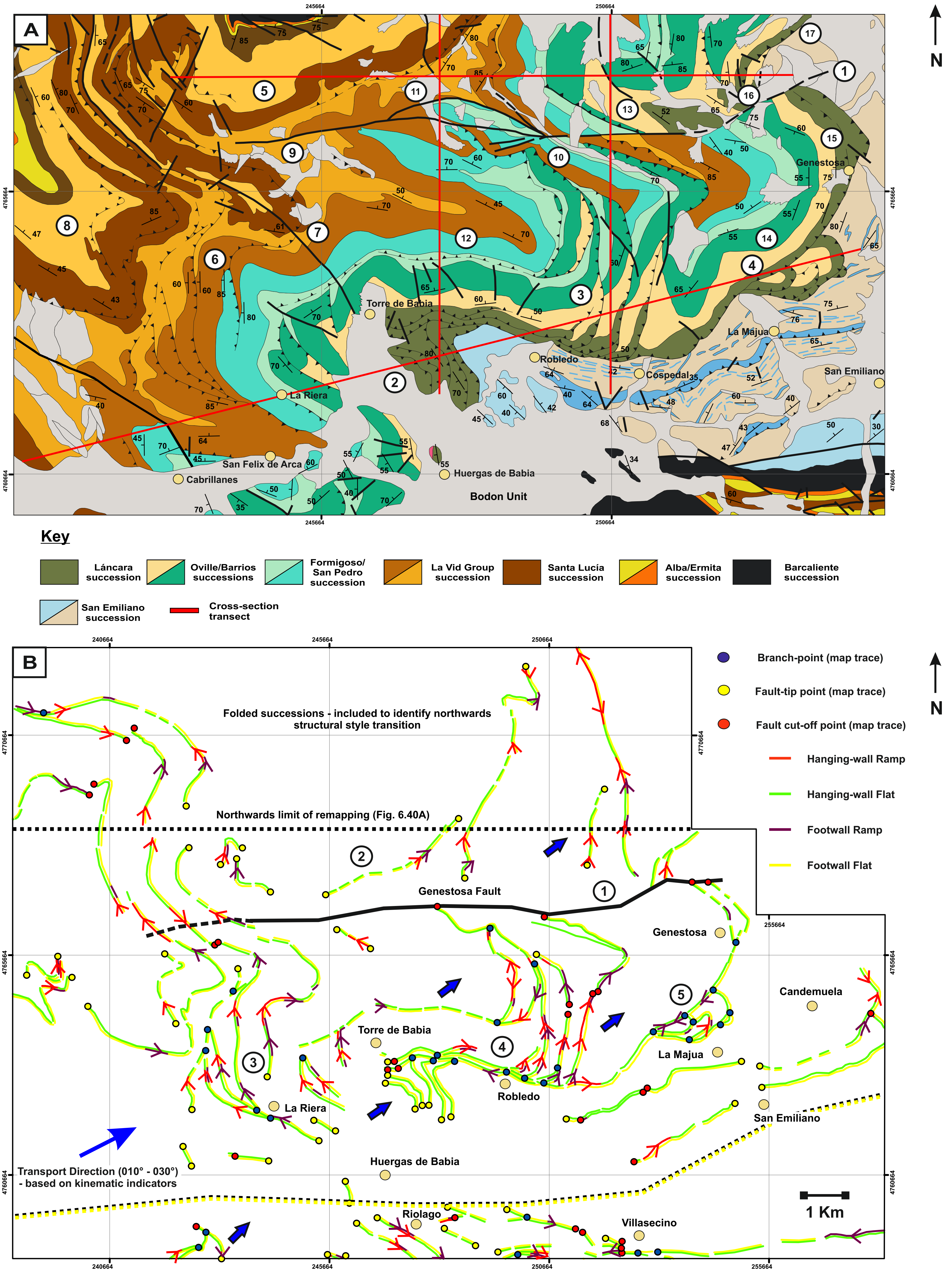


Figure 6.40: (A) Geological map of the transition domain northern hinge comprising the northern sections of the Barrios de Luna geological map and the southernmost portions of the La Plaza geological map (Suárez *et al.*, 1991 and Marcos *et al.*, 1980). Map updated during detailed ground-truthing and localised re-mapping. Locations of transport-parallel and transport-lateral cross-sections highlighted. A distinct cross-strike change is identified across the Genestosa Fault. Observations highlighted within the text numbered. **(B)** Fault network analysis of the northern hinge of the transition domain. A distinct compartmentalisation is identified between the southern and northern walls along the Genestosa Fault. Observations highlighted within the text are numbered, whilst transport kinematics are highlighted (blue arrows).

Thrust lateral climb up-section (i.e., thrust facing):
Hanging-wall ramp
Footwall ramp

developed with only a few thrusts, such as the Somiedo Sole Thrust, present within map view (Figure 6.40a [5]; 6.40b [2]).

Within the southern wall of the Genestosa Fault, northwest of the town of La Riera (UTM 29N, 4511 7620) and Torre de Babia (UTM 29N, 4664 7635), a series of folded thrusts within La Vid Group successions are observed stratigraphically climbing northwards into Santa Lucía Formation limestones forming the La Pradera hillside and the Picos Albos Mountain (UTM 29N, 4486 7654; Figure 6.40a [6, 7]; 6.40b [3]; 6.41). Geometrical and kinematic indicators (i.e., thrust hanging-wall anticlines and asymmetric cleavages) within these splays, and orientations of large-scale map-view folded successions within structurally higher thrust sheets, indicate a top-to-north-northeast (010° to 030°) transport direction for the La Riera and Torre de Babia region (Figure 6.41a; 6.41b; 6.41c). Hinterlandward structurally higher thrusts carry large folded sequences of higher stratigraphical units (i.e., Devonian Santa Lucía Formation limestones to Carboniferous Barcaliente limestones; Figure 6.40a [8]). Within a three dimensional context, map patterns comprising these stratigraphical higher units reside within a higher décollement at the base of the La Vid Group which are back-steepened as a result of interactions with forelandward structures (Figure 6.42b [1]).

Interactions of these structurally and stratigraphically higher units within the region of the Genestosa Fault (Figure 6.40a [9]; 6.43a) indicate considerable deformation, with large folds in various orientations indicating transpressive deformation against the map-view location of the Genestosa Fault (Figure 6.43b; 6.43c). Numerous springs are also identified within these deformation zones (Figure 6.44).

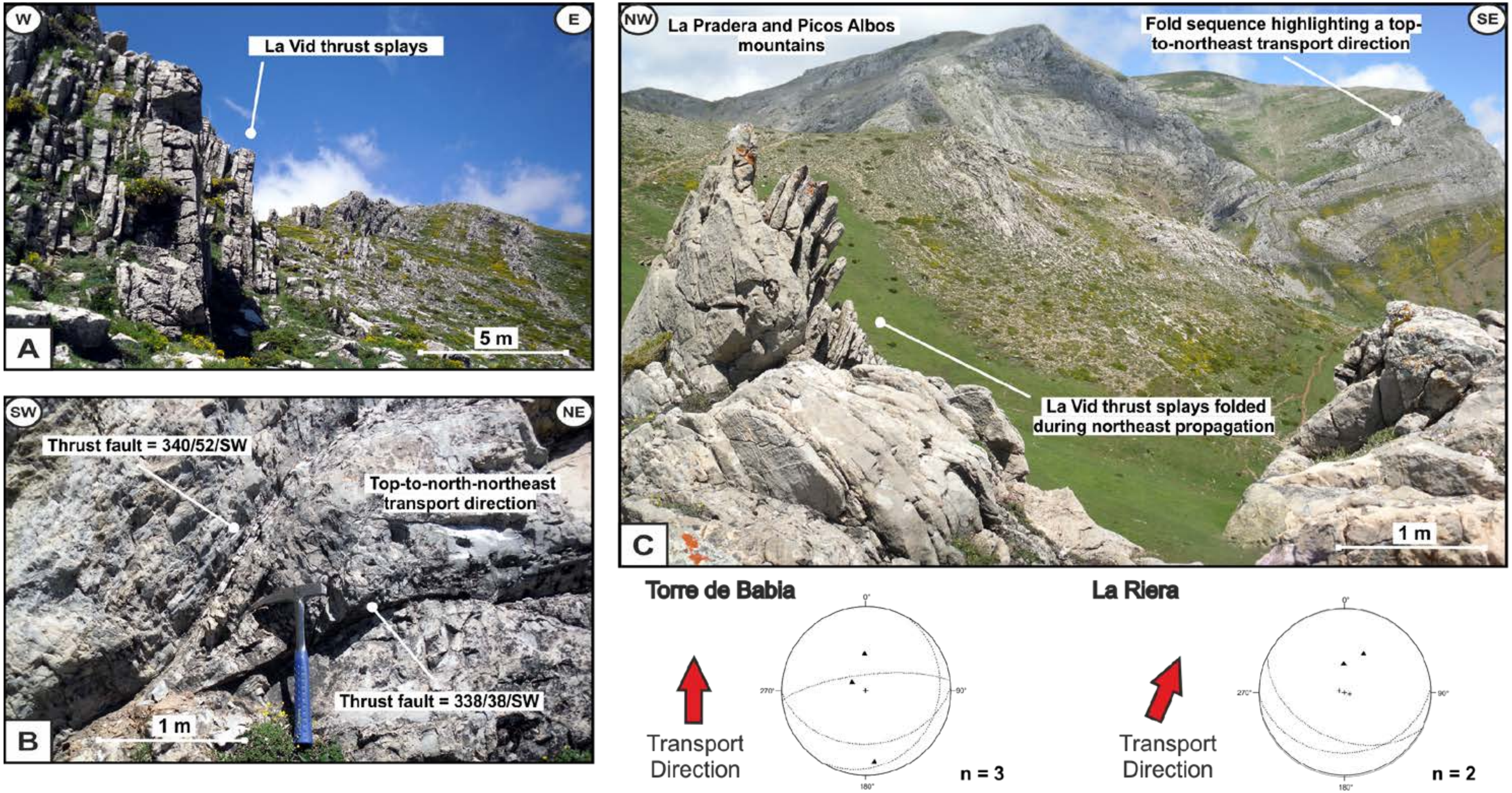
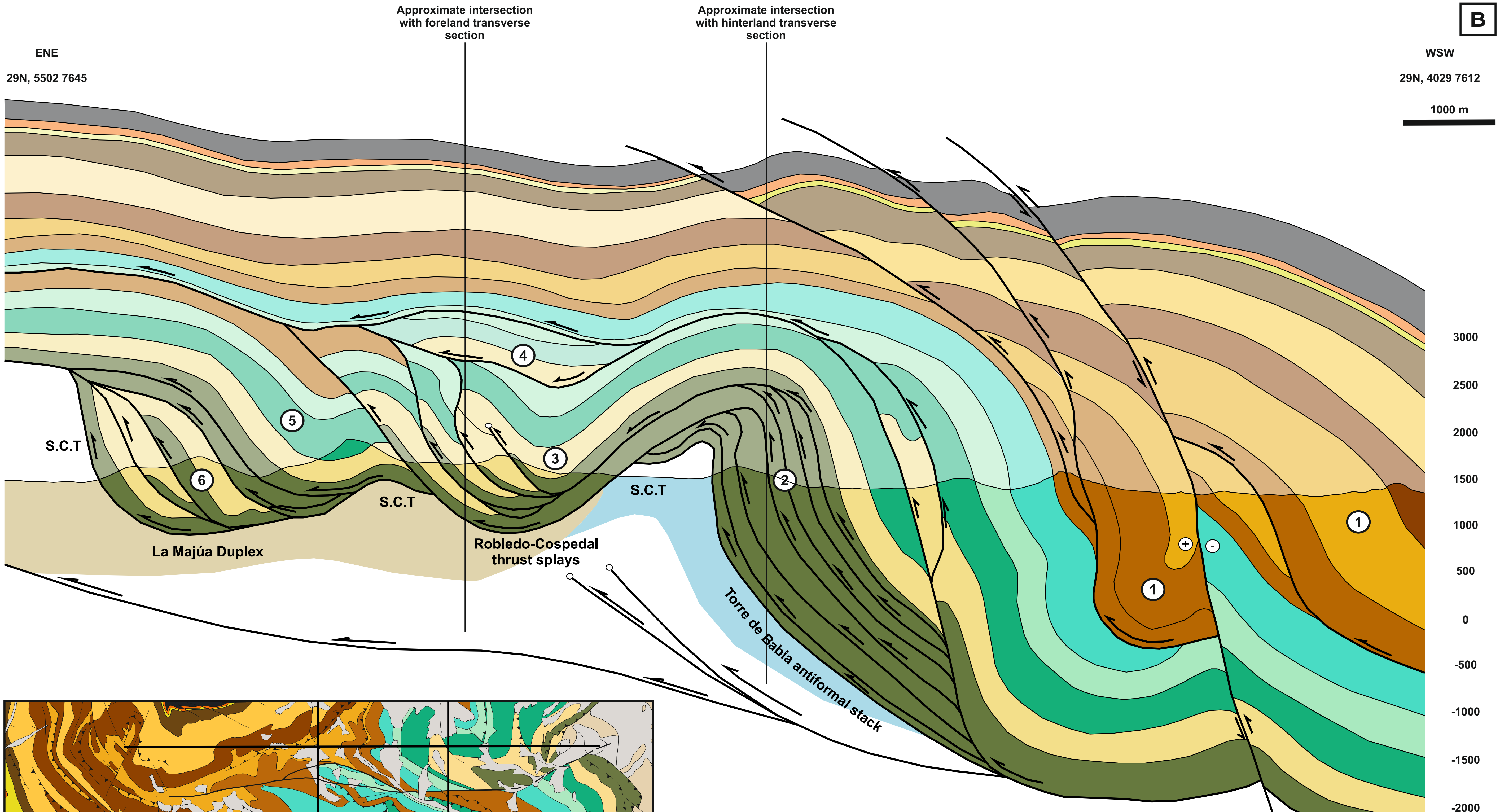
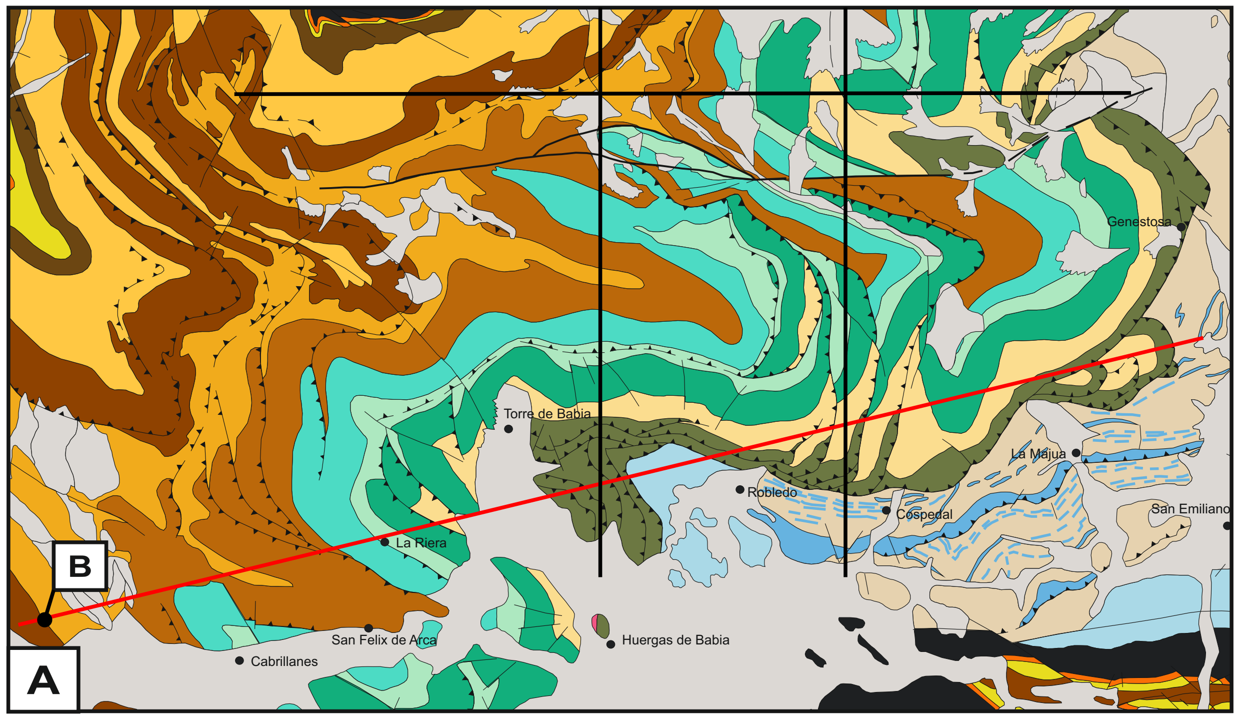


Figure 6.41: **(A)** Thrust splays above La Riera and Torre de Babia climbing from La Vid Group lithologies into Santa Lucía limestones. **(B)** Thrusts highlight a top to north to north-northeast (010° - 030°) transport direction within this region once Iberian rotation is removed. **(C)** Large-scale structures within the Santa Lucía Formation dominant La Pradera hillside and Picos Albos Mountain support small-scale observations in the form of large fold trains, which indicate a top-to-northeast transport direction (n = number of observations [poles to thrust planes]).





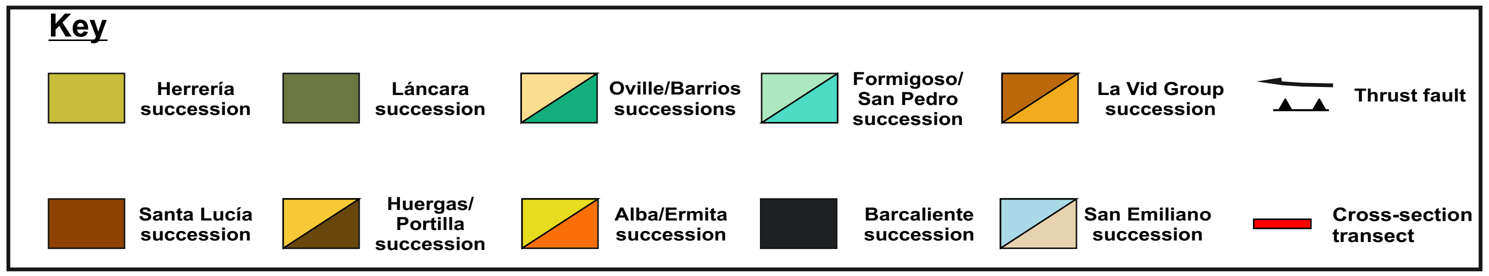


Figure 6.42: **(A)** Geological map updated during ground-truthing and small-scale remapping highlighting cross-section locations (Adapted after Marcos *et al*., 1980 and Suárez *et al*., 1991). **(B)** Transport-parallel cross-section highlighting the Genstosa Fault southern wall forelandward development, including developments of the Torre de Babia antiformal stack, the Robledo-Cospedal thrust splays, and the La Majúa duplex. Development of these structures indicates elements of transpression and buttressing within the southern wall. Individual observations identified within text are numbered, whilst approximate positions of intersecting transport-lateral cross-sections are also identified. (S.C.T = Somiedo-Correcillas 'Sole' Thrust).

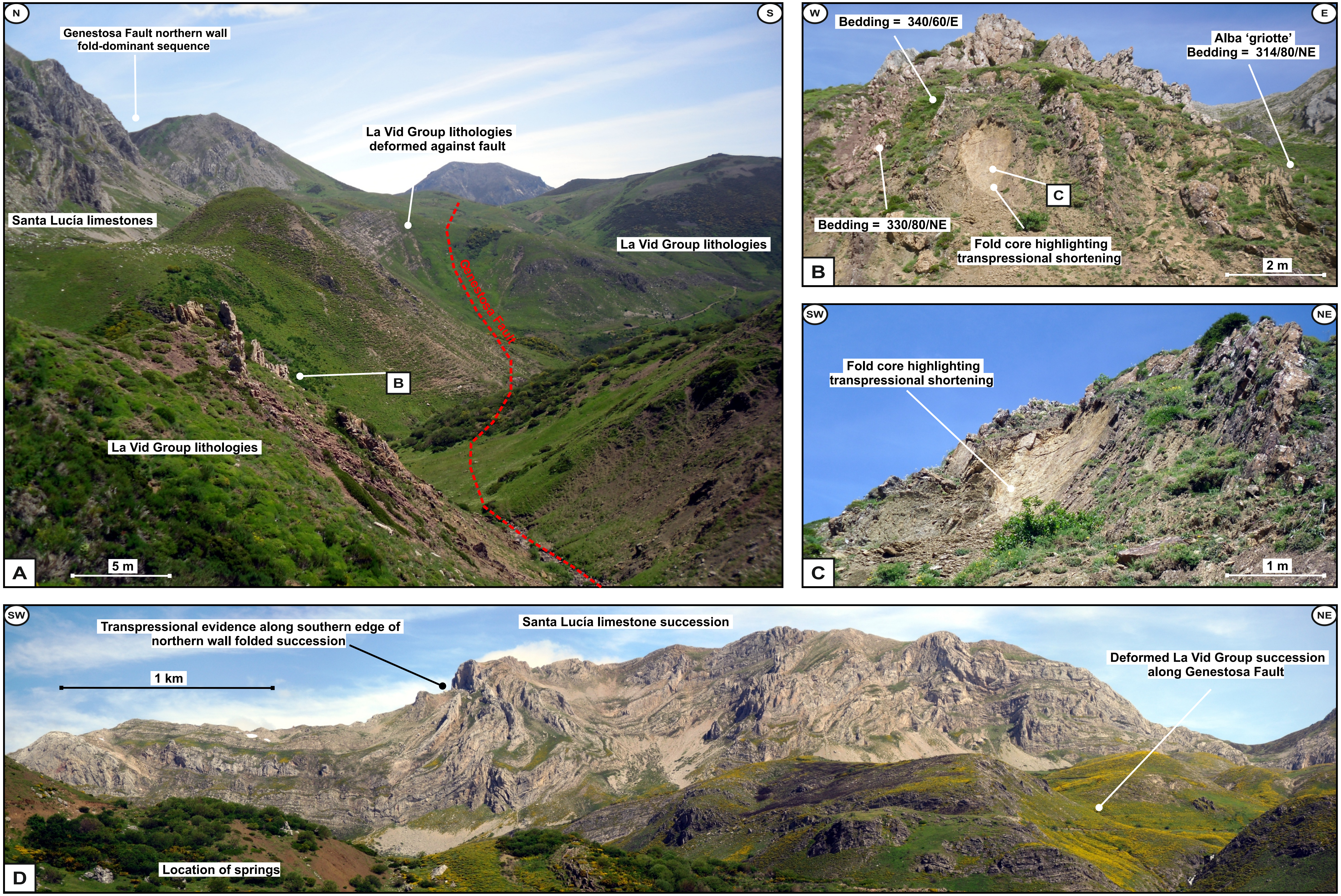


Figure 6.43: **(A)** Hinterland sections of the Genestosa Fault above La Riera and Torre de Babia. Scales relevant to foreground units. **(B, C)** Transpressional evidence is identified along the edge of the Genestosa Fault within La Vid Group lithologies. Further evidence on a larger scale of transpressional deformation is identified within the northern wall of the Genestosa Fault, where Santa Lucía limestones interact with the edge of the Genestosa Fault **(D)**.

Western (hinterlandward) regions of the Genestosa Fault above La Riera and Torre de Babia,
Transition domain northern hinge, [UTM 29N, 4549 7663]

Figure 6.44: Series of small springs identified within La Vid Group lithologies. Springs are localised to deformation areas along the Genestosa Fault southern wall hinterland. Scale = Hammer (30 cms).

Conversely, within the northern wall of the Genestosa Fault, large-scale folds comprising Santa Lucía limestones, Huergas, Portilla, Ermita and Alba formation siltstones, sandstones and limestones and Barcaliente limestones of the Peña Orniz hillside replace thrust splays identified within the southern wall (Figure 6.40a [5]). Transpressive deformation is identified along the southern edge of these folds indicating interactions with the Genestosa Fault (Figure 6.43d). Within a three-dimensional context, successions within the northern wall of the Genestosa Fault are contained within a single much thicker thrust sheet than those within the Genestosa Fault southern wall indicating further compartmentalisation either side of the Genestosa Fault (Figure 6.45b [1]).

Forelandward of these successions, a large antiformal stack comprising Láncara Formation dolostones is identified south of the town of Torre de Babia (i.e., the Torre de Babia antiformal stack; UTM 29N, 4771 7628; Figure 6.40a [2]; 6.42b [2]). Although individual thrust splays are hard to identify, stratigraphical thicknesses of this structure require at least seven thrust splays to be present. Transport-lateral cross-sections through

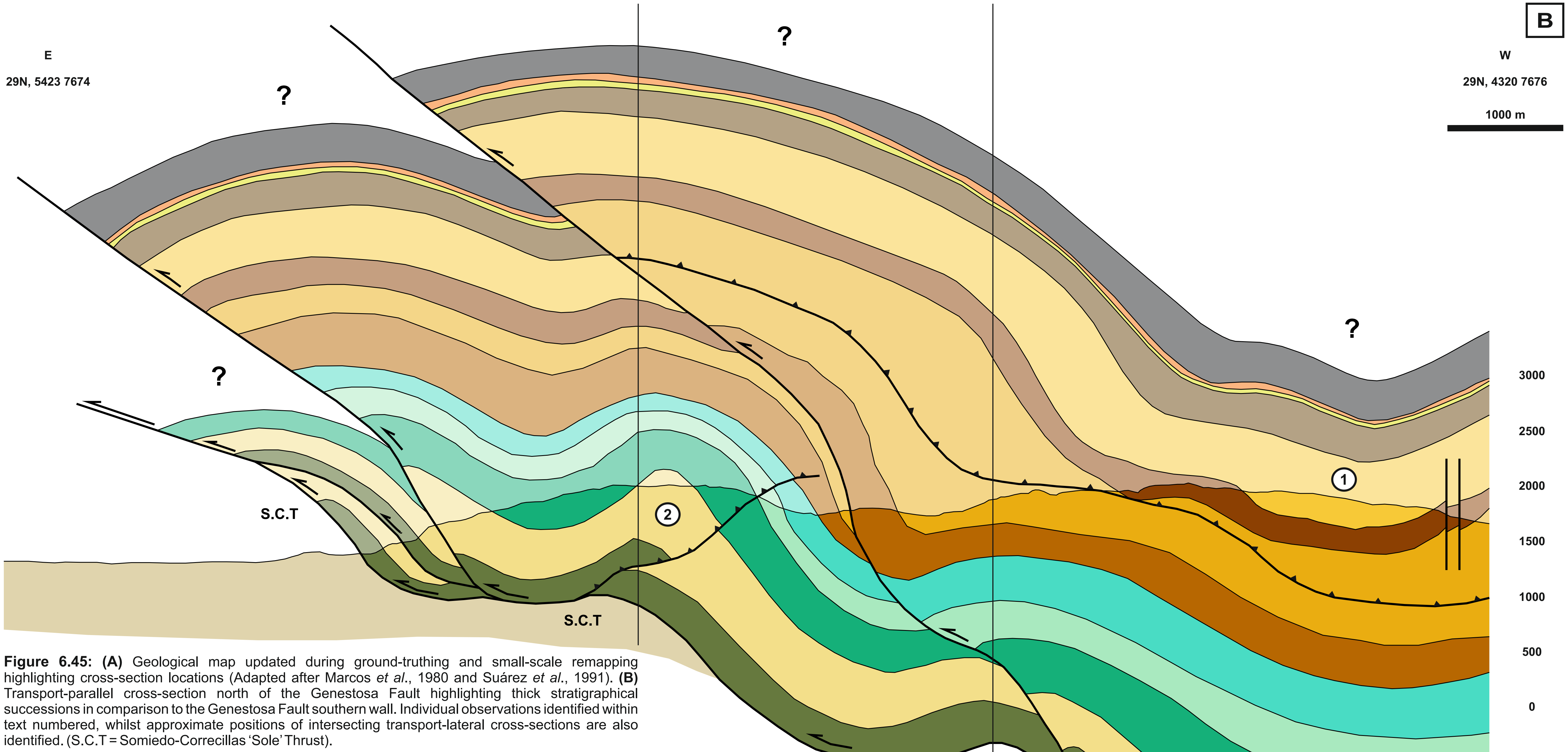
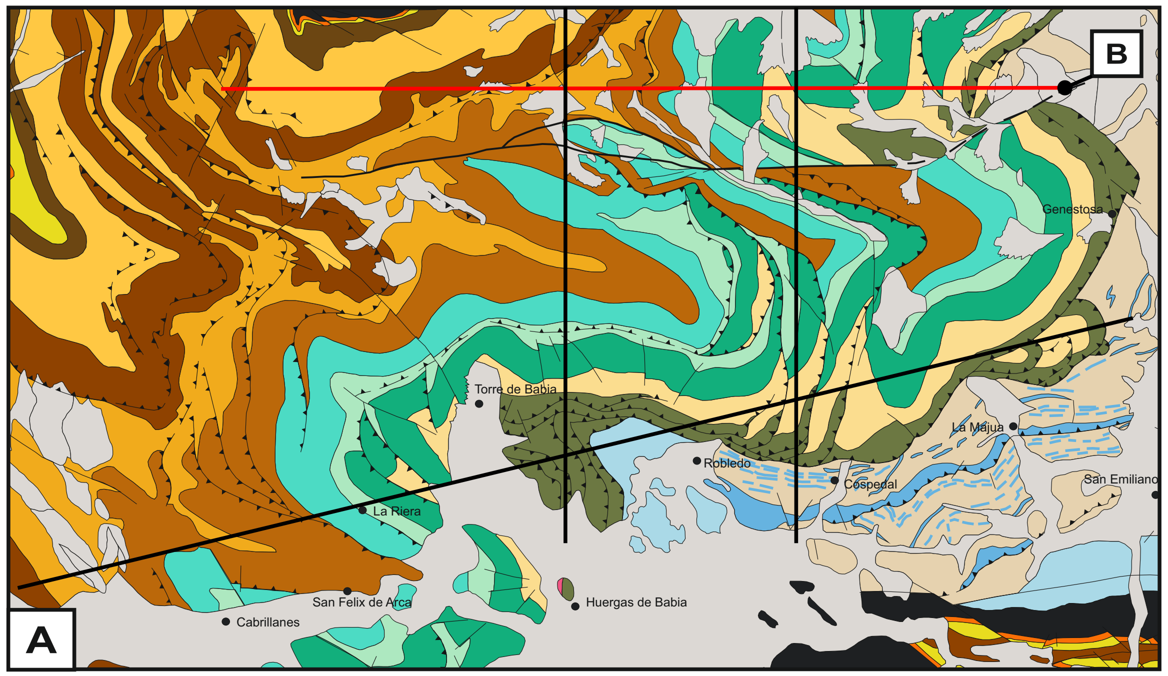
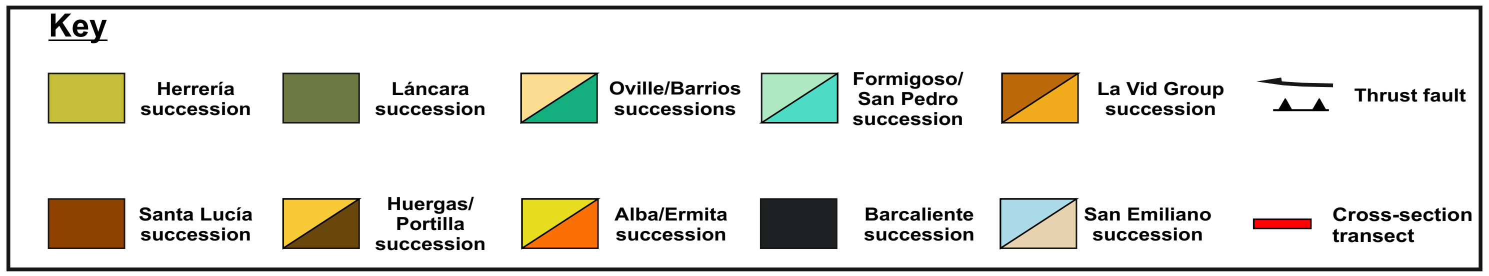


Figure 6.45: (A) Geological map updated during ground-truthing and small-scale remapping highlighting cross-section locations (Adapted after Marcos *et al*., 1980 and Suárez *et al*., 1991). **(B)** Transport-parallel cross-section north of the Genestosa Fault highlighting thick stratigraphical successions in comparison to the Genestosa Fault southern wall. Individual observations identified within text numbered, whilst approximate positions of intersecting transport-lateral cross-sections are also identified. (S.C.T = Somiedo-Correcillas 'Sole' Thrust).





the Torre de Babia antiformal stack (Figure 6.46a [1]) northwards across the Genestosa Fault indicate large-scale transpressional structures (e.g., positive 'flower' structures; Figure 6.46a [2]) which develop as splays off the Genestosa Fault within the southern wall (Figure 6.40a [10]). Within the northern wall of the Genestosa Fault, splays of the Genestosa Fault truncate the hinterland sequence producing localised transpressional folds (Figure 6.40a [11]; 6.46a [3, 4]).

Thrusts forming the Torre de Babia antiformal stack propagate forelandward into a series of thrust splays (i.e., the Robledo-Cospedal splays; Figure 6.40a [3]; 6.42b [3]; 6.46b [1, 2, 3]) which stratigraphically cut up-section northwards along a series of branch-lines from Láncara Formation dolostones to La Vid Group lithologies (Figure 6.40a [3, 10]; 6.42b [4]; 6.46b [1, 2, 3]). Asymmetrical cleavage and a schistosity plane fabric developed within Láncara Formation 'Griotte' limestones along the Robledo-Cospedal thrust splays indicate a top-to-northeast transport direction (Figure 6.47).

Analyses of map patterns, the fault network, and cross-sections through the Robledo-Cospedal splay system indicate an out-of-sequence development with structurally higher splays truncating lower thrust splays producing numerous hanging-wall and footwall ramp sequences (Figure 6.40a [3] ;6.40b [4]; 6.46b [1, 2, 3]). The Robledo-Cospedal Thrust splay series is subsequently truncated by a structurally higher thrust within the Formigoso Formation black graptolitic shales and intercalated siltstones which is deflected over the 'flower' structures developed along the Genestosa Fault (Figure 6.40a [12]; 6.42b [4]; 6.46b [4]). Within the Genestosa Fault northern wall, a localised back-thrust truncates folded Láncara Formation dolostones to San Pedro Formation sandstone successions developed against the Genestosa Fault indicating a forelandward transpressional development (Figure 6.40a [13]; 6.45b [2]; 6.46b [5]).

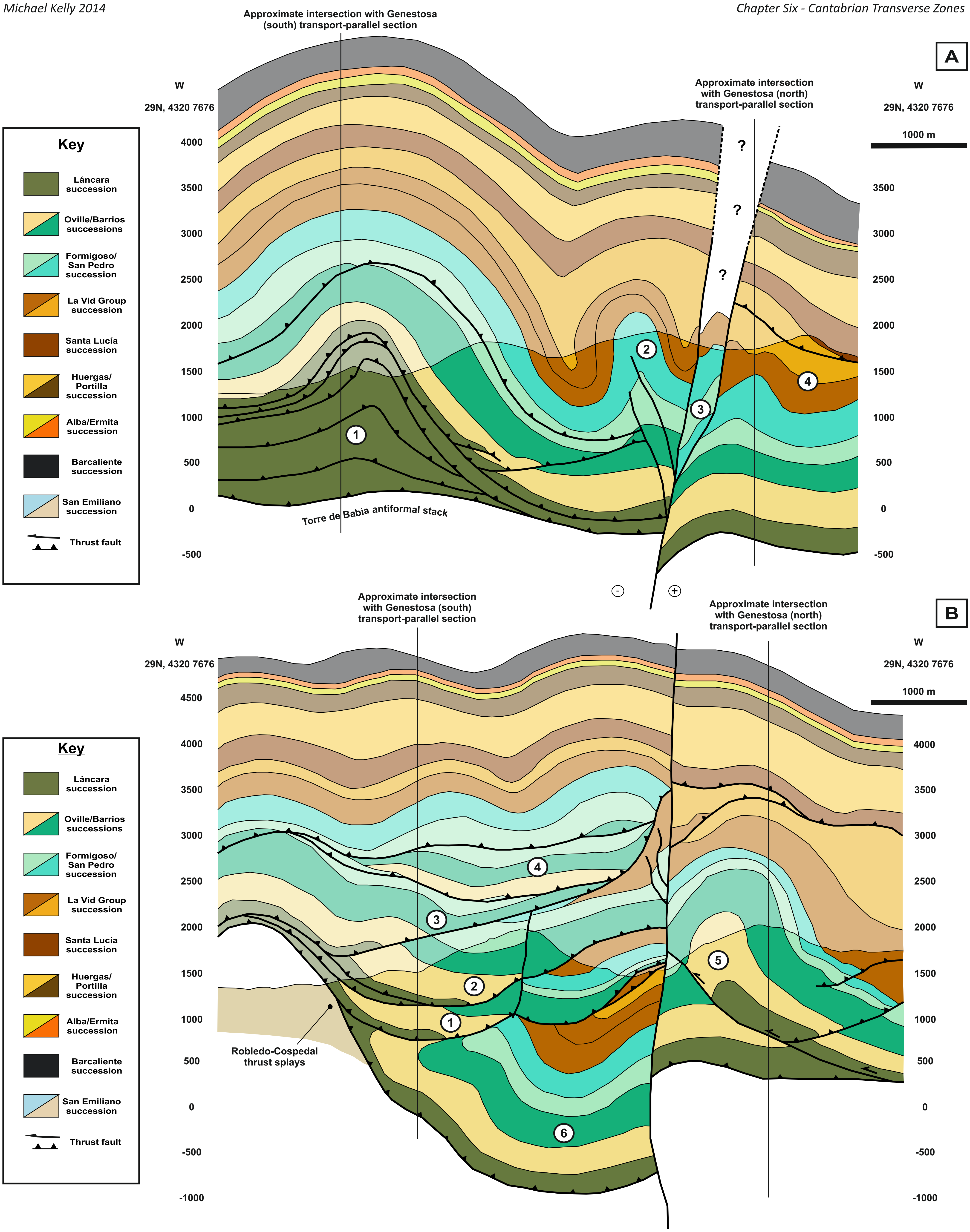


Figure 6.46: Transport-lateral cross-sections through the Genestosa southern and northern walls. Locations of these cross-sections are identified within Figure 6.40. **(A)** Within hinterlandward sections of the Genestosa Fault, evidence of transpressional deformation and the production of positive 'flower' structures is identified. Transpressional deformation occurs as a result of interactions between cover strata and potential sub-decollement structures producing the Torre de Babia antiformal stack and splays of the Genestosa Fault. **(B)** Sequence develops forelandward into the Robledo-Cospedal thrust splays which indicate an out-of-seqwuence development, truncating underlying thrust sheets. A clear disparity between the structural height of the Somiedo-Correcillas Sole Thrust south to north is also observed.

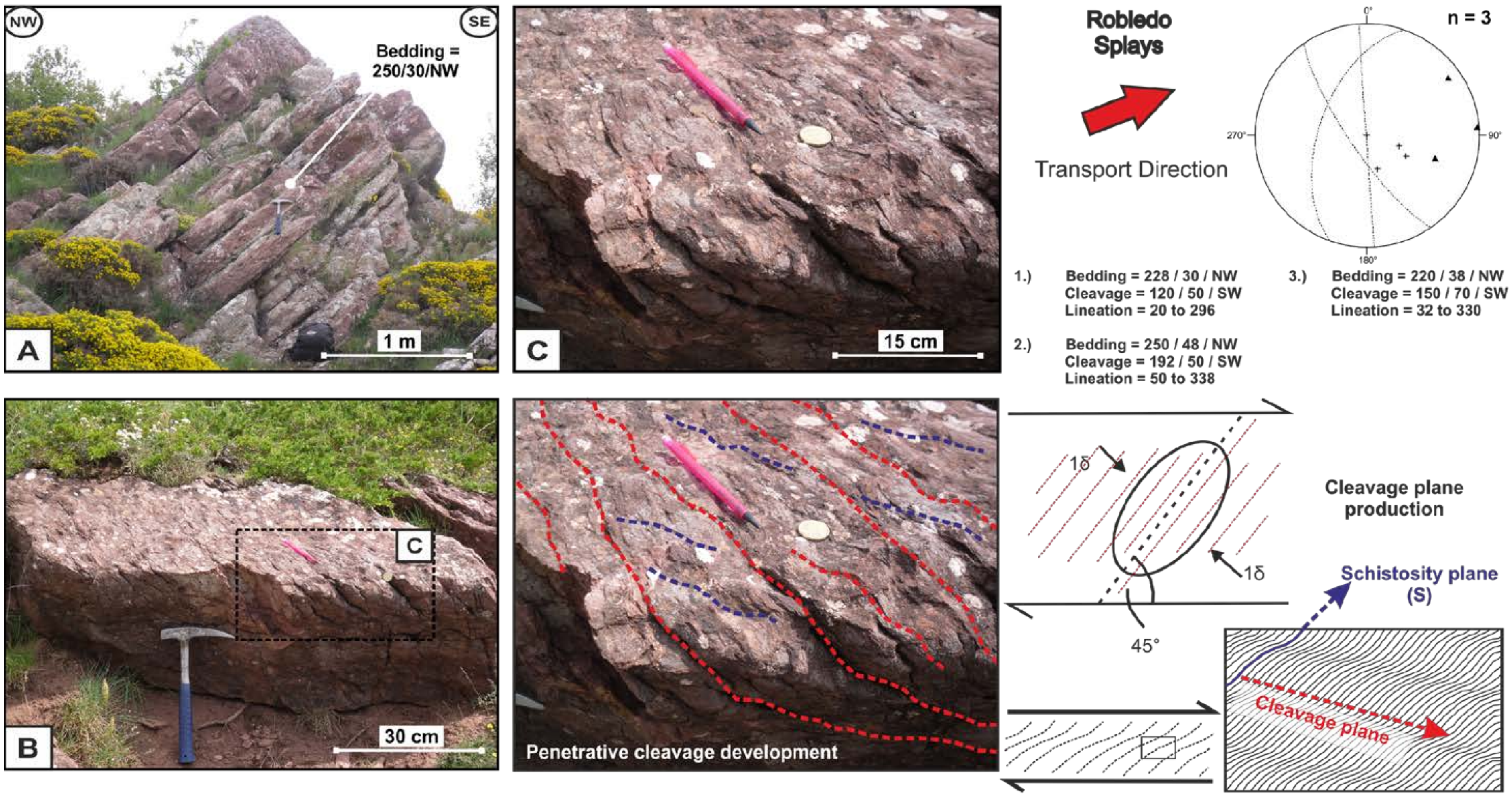


Figure 6.47: (A, B) Láncara Formation 'Griotte' limestones along the Robledo-Cospedal thrust splays. **(C)** Development of an asymetric cleavage (red lines) and a schistosity plane (purple lines) within the Láncara Formation 'Griotte' limestones indicate a top-to-northeast transport direction for the Robledo-Cospedal thrust splays once Iberian rotation is removed (30°) (n = number of observations [poles to cleavage]).

Forelandward of the Robledo-Cospedal Thrust splays, a large thrust sheet comprising Láncara Formation dolostones to La Vid Group lithologies is identified within the Genestosa Fault southern wall (Figure 6.40a [14]; 6.42b [5]). Map-view expressions of these successions indicate both east-west and north-south shortening, whilst transport-lateral cross-sections indicate that the Somiedo-Correcillas Sole Thrust within the Genestosa Fault southern wall cuts five hundred metres deeper into the foreland than the northern wall (Figure 6.46b [6]). Within the footwall of the Somiedo-Correcillas Sole Thrust, the La Majúa duplex is identified west of the town of Candemuela (UTM 29N, 5569 7637; Figure 6.40a [4]; 6.42b [6]). Map pattern observations and cross-sections through the La Majúa duplex indicate that structurally higher thrusts carrying Láncara Formation dolostones display elements of an out-of-sequence development, truncating internally folded thrusts and producing several footwall ramps (Figure 6.40a [4]; 6.40b [5]).

The Somiedo-Correcillas Sole Thrust develops northwards into two branches along the forelandmost expression of the Genestosa Fault north of the Genestosa village (UTM 29N, 5484 7660; Figure 6.40a [15]; 6.48a). Within the forelandmost regions of the Genestosa Fault, numerous fault splays are identified indicating that the Genestosa Fault develops from a single fault plane above Torre de Babia, to a series of fault splays which truncate and displace stratigraphical successions within the northern wall and southern walls, producing isolated lense structures. Kinematic indicators within truncated units and along individual lenses indicate a dominant sinistral transport (Figure 6.40a [16]; 6.48b-e). The Somiedo-Correcillas Sole Thrust is displaced six hundred and seventy five metres westwards before continuing north-eastwards (Figure 6.40a [17]; 6.48f). No kinematic indicators are identified within these northern Láncara Formation units.

Within the northern regions of the transition hinge domain, a distinct compartmentalisation

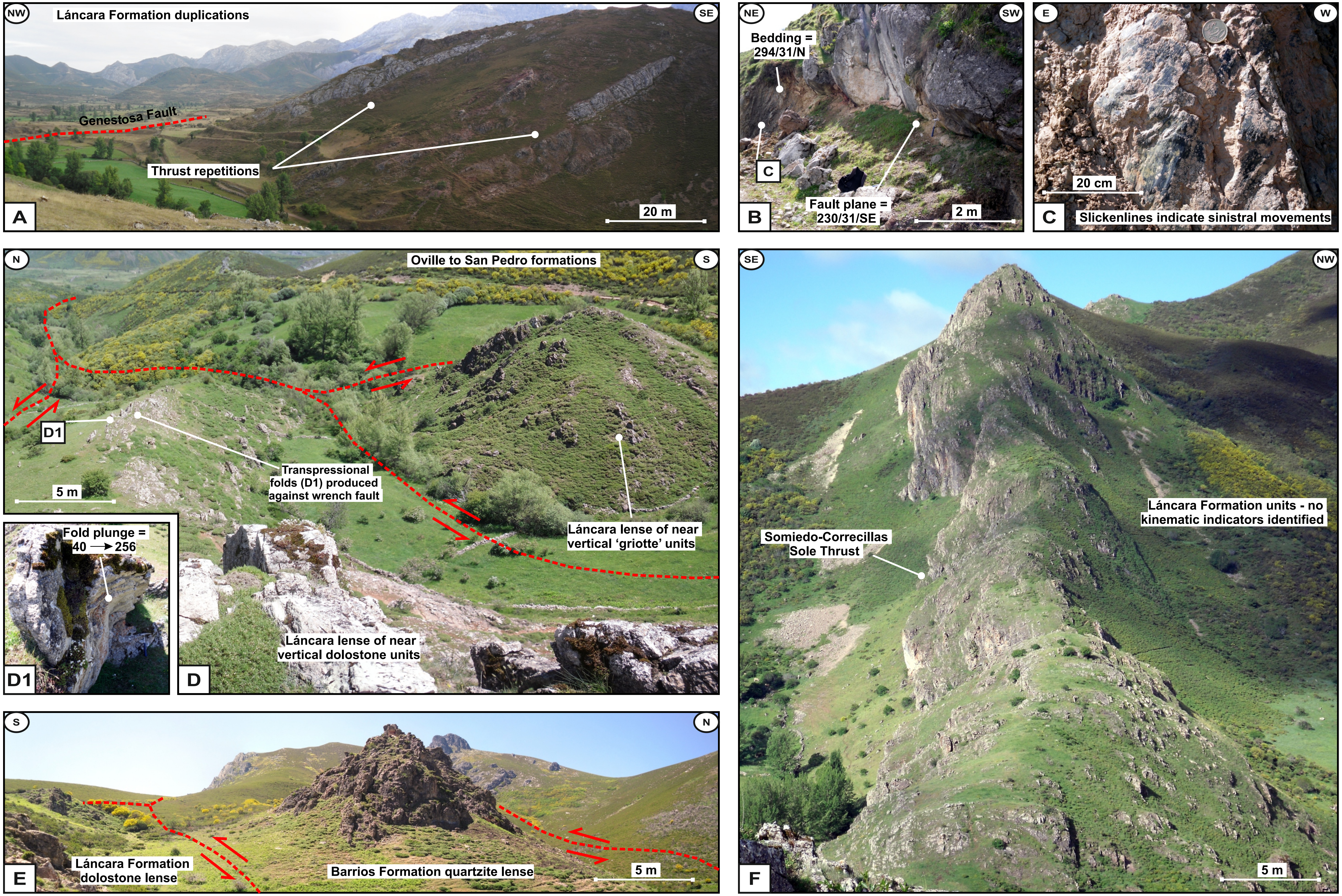


Figure 6.48: (A) Láncara succession duplications south of the Genestosa Fault. **(B, C)** Truncation of Oville Formation siltstones and sandstones against the Genestosa Fault. Slickenside evidence within units highlights a sinistral movement direction for the Genestosa Fault. **(D, E)** Within frontal sections of the Genestosa Fault, numerous fault splays are observed producing lenses of Láncara Formation dolostones and Barrios quartzites. **(F)** North of the Genestosa Fault, the Somiedo-Correcillas Sole Thrust continues northeastwards carrying Láncara Formation lithologies. No kinematic indicators are identified within these units.

Eastern (forelandward) regions of the Genestosa Fault north of Genestosa, Transition domain northern hinge, [UTM 29N, 5216 7670]

of structures is therefore identified across the Genestosa Fault. Within the southern wall, large-scale examples of transpression and buttressing are identified producing antiformal stacks, duplexes and positive ‘flower’ structures, whilst thrust splays developed within the southern wall indicate an out-of-sequence development. Transport directions within this southern wall support transpressional deformations.

A sub-décollement structure within the present day Huergas de Babia valley is suggested to bound the southern edge of the Genestosa Fault southern wall, while the Genestosa Fault *senso stricto* bounds the northern edge resulting in focussed deformation between the structures. The Genestosa Fault separates this focused area of deformation in which numerous thrust splays are produced, from a northern wall comprised only a few dominant thrusts, within which large folded successions are developed. These successions develop northwards into the fold-dominant northern domain. The Genestosa Fault therefore represents a long-lived structure along which deformation is compartmentalised.

6.3.3.4. Transition hinge domain: Summary

Within the transition hinge domain, a series of along-strike and cross-strike discontinuities are identified within the northern and southern hinges along a distinct westward concavity of the Somiedo-Correcillas Sole Thrust. The southern hinge is characterised by three distinct zones (Figure 6.30):

(1) A zone dominated by transport-aligned thrust ramps within the Embalse de Los Barrios de Luna region,

(2) A zone dominated by numerous transport-aligned thrust bifurcations, evidence for both east-west and north-south compression in the form of reactivated or truncated

relict structures, and the formation of a large, northeast-plunging, folded thrust within the forelandward Bodon Unit,

(3) Formation of a 'bevelled' zone, within which numerous thrust splays, thrust ramps (i.e., the La Casa ramp series) and radiating folds are produced. A series of thrusts indicate later reactivations truncating forelandward structures orientated ninety degrees to the thrust front. Numerous examples of mineralisation are also focused within the southern hinge along this 'bevelled' zone.

Conversely, the northern hinge is dominated by compartmentalisations of large-scale transpressional structures forming antiformal stacks, thrust splays and duplexes within the southern wall of the Genestosa Fault, whilst its northern wall is dominated by folded successions developed within the hanging-walls of only a few dominant thrusts. The Genestosa Fault is therefore a long-lived structure which compartmentalised deformation (Figure 6.40). The core of the hinge domain is dominated by a large east-north-east to west-southwest orientated conical fold which is transected by later wrench faults. Development of disparities within the northern and southern regions of the transition hinge domain led Nijman & Savage (1989) to suggest a sub-décollement compartmentalising structure.

This current research suggests that structural developments within the southern and northern sections of the transition hinge domain are kinematically linked to the development of the conical fold within the hinge core identified by Pastor Galan et al., (2012) and its links to major frontal structures such as the Léon Fault. Therefore, there is sufficient evidence to suggest that this domain is a potential large-scale transverse zone.

6.4. Discussion

Although numerous individual structural disparities have been identified, a distinct paucity of research to identify cross-strike discontinuities aligned within the transport direction has been undertaken within the Cantabria-Asturian Arc, with the notable exception of Nijman & Savage (1989). This paucity in research may be explained by the lack of constraint upon the development of the pre-Variscan passive margin successions and structures, and syn-kinematic responses to this architecture (i.e., thrust sheet rotations during oroclinal bending), culminating in complex map-patterns (e.g., Keller *et al*., 2008). Therefore only potential transverse zones / cross-strike discontinuities can be identified.

Within this current research, several potential cross-strike discontinuities have been identified over various scales within the Cantabria-Asturian Arc. These include the Villamanín Transverse Structure / Lateral Ramp within the southern domain and a series of discontinuities comprising the transition 'hinge' domain (Figure 6.11). No cross-strike discontinuities are identified within the northern domain of the Somiedo-Correcillas Unit. The development of these identified cross-strike discontinuities is indicative of the multiphase development of the Cantabria-Asturian arc and the Somiedo-Correcillas Unit as a whole during oroclinal development.

6.4.1. Suggested development of potential cross-strike discontinuities / transverse zones within the Somiedo-Correcillas Unit

During the Moscovian Period (Early Carboniferous), compressional deformation from the Variscan Orogeny produced a series of eastward-propagating thrusts (modern day orientation; Kollmeier *et al*., 2000; Weil et al., 2000; 2001; 2010). These Variscan north-south orientated thrusts are still observed within the central to northern sections of the

Somiedo-Correcillas Unit forming the fold-dominant regions of the northern domain which comprise thrust sheets up to 4.75 kilometres thick (Figure 6.8; 6.10). During the Late Stephanian (Gzhelian) to Early Permian, a change to a north-south compression is identified accommodated by vertical axial rotations within the core of the Cantabrian Zone (Parés *et al*., 1996; Weil *et al*., 2000; 2001; 2010; Gutiérrez-Alonso *et al*., 2004; Pastor-Galán *et al*., 2011; Johnston *et al*., 2013). It is during this period that cross-strike discontinuities identified within this research within the transition hinge domain are suggested to have been produced.

During Early Permian oroclinal bending, this research suggests that a location for vertical axial rotations was focused north of the transition hinge domain, supporting observations by Pastor Galan *et al*., (2012). During the rotation of the southern arm of the Cantabria-Asturian Arc, a large conical fold was produced within the core of the hinge (e.g., Pastor Galan *et al.,* 2012; Figure 6.30a [18, 19]). Development of this fold and continued east-west compression compartmentalised deformation within the northern and southern hinges. Within the northern hinge, formation of the Torre de Babia antiformal stack and the Robledo-Cospedal splays are suggested to have occurred as a result of buttressing against this fold. Development of the Robledo-Cospedal thrust splays is indicative of a sidewall duplex, developed against the northern limb of the conical fold (Figure 6.49).

The effects of buttressing are amplified against the Genestosa Fault, resulting in transpressional deformation and a much deeper Sole Thrust (i.e., Somiedo-Correcillas Thrust) within the southern wall of the Genestosa Fault (Figure 6.46b [6]). The Genestosa Fault is suggested within this research to be a long-lived structure separating much thicker stratigraphical successions comprising larger sedimentary basins within the northern wall, from smaller basins within the southern wall.

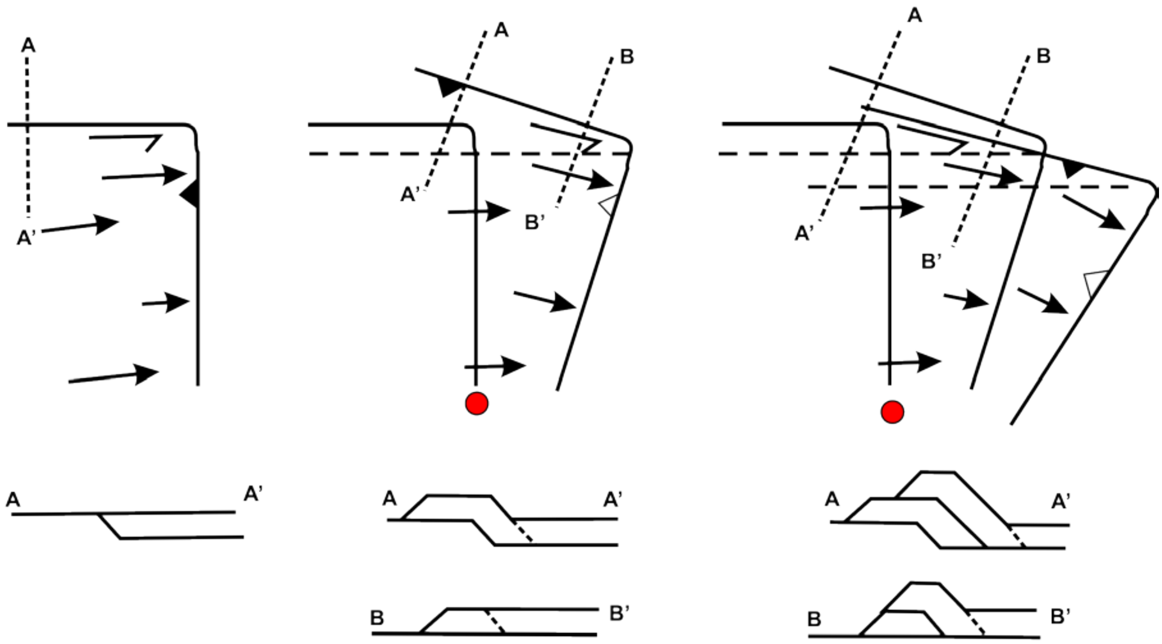


Figure 6.49: Development of a sidewall duplex as illustrated within map-patterns of the Robledo-Cospedal thrust splays (greater detail provided within Chapter two).

Within the southern hinge, structures produced during oroclinal bending include the formation of the large northeast-plunging folded thrust (Figure 6.30a [13]) identified within the Bodon Unit and a series of folded thrusts within the Penalba de Cilleros region (Figure 6.30a [16]). However, further evidence of oroclinal bending within the southern hinge is removed by later thrust reactivations during later north-south compression phases which reactivate thrusts within the southern hinge and tighten the hinge further. Evidence for these reactivations is identified within the Abelgas valley where transpressional folds and truncated relict extension faults are identified. The development of the 'bevelled' zone is suggested to be the reactivation front for this secondary phase of thrusting within the hinge zone, truncating underlying structures produced during early phases of oroclinal bending (Figure 6.30a [15]).

Nijman & Savage (1989) suggested that a northeast-southwest orientated lineament, the Aralla Lineament, transected this transition hinge domain compartmentalising deformation

(Figure 6.30). This research supports the location of the Aralla Lineament. However, no evidence is identified for a sub-décollement structure within the Huergas de Babia Valley beyond the formation of the conical fold. Several authors, predominantly from the University of Leiden (e.g., Savage & Boschma, 1980) have suggested that a south-western arm of the Léon Fault may be present within this valley, but no evidence for this structure is identified.

Continuing eastwards from the southern hinge domain into the southern domain, a series of aligned thrust bifurcations are identified highlighting a potential sub-décollement structure south of the village of Villamanín, (i.e., the Villamanín Transverse Structure). Map-patterns suggest that this structure comprises a lateral ramp connecting the frontal Somiedo-Correcillas Sole Thrust to two frontal ramps comprising the Hoces de Vegacervera and Gete branches of the Somiedo-Correcillas Sole Thrust (Figure 6.20a [4]). Structures such as the Rodiezmo antiformal stack are produced at the interactions of these structures (Figure 6.20a [10]).

Within the southern domain, structures such as the Cueto Negra-Brañillín Window within the southern wall of the Léon Fault highlight a dominant northwards transport. This research suggests that this northwards transport comprises Early Permian north-south compression which reactivated early extension faults orientated favourably to transport. However, later reactivations of east-west striking thrusts during the Alpidic Orogeny cannot be discounted. Therefore, potential sub-décollement structures within this southern domain are suggested to be syn-kinematic in nature produced during Early Permian or later deformation events.

Nijman & Savage (1989) suggested that the development of complexities, such as the Rodiezmo antiformal stack along the Somiedo-Correcillas Sole Thrust, and the formation of the Cueto Negra-Brañillín Window were indicative of a second northeast-southwest lineament (i.e., the Luna Lineament). This research highlights several transport aligned thrust ramps within the Embalse de Los Barrios de Luna region. However, this research suggests that localisation of complexities within the southern domain is due to the interaction of frontal and lateral ramps along the Somiedo-Correcillas Sole Thrust front. The location of the Cueto Negra-Brañillín Window is suggested to be linked to inversion during northwards transport across the reactivated Léon Fault and the location of the conical fold developed further to the west. No evidence for the Luna Lineament is therefore highlighted within this research.

To determine whether observed discontinuities are indicative of a transverse zone within the transition hinge zone, Wheeler's (1980) criteria of transverse zones identification was implemented (Table 6.1). Results indicate that out of twenty criteria utilised for transverse zone identification, the transition hinge domain complies with twelve of these criteria. Therefore the transition hinge domain should be considered as a large-scale transverse zone.

Transverse zone identification criteria	Evidence
1. Along-strike terminations/curves/offsets of detached folds, longitudinal thrust faults and/or ramp anticlines…	Hinge & Southern Zones
2. Presence of a small fold or fault that records larger movements…	Genestosa Fault (HZ)
3. High joint intensity within a section, a large size, close spacing or combinations of the two…	N / A
4. Development of intense cleavage…	Torre de Babia, Robledo (Griotte) (HZ)
5. Transverse faults, particularly if movement occurred at more than one time, in more than one direction, or a combination of both (sub-décollement basement faults / basement-rooted faults in cover strata…	Genestosa Fault (HZ)
6. Anomalous changes in contours of smoothed values of dip or strike of particular beds…	N / A
7. Changes in orientation of structural grain…	Hinge Zone
8. Abrupt changes in depth to magnetic basement / disruptions in magnetic or gravity anomalies, particularly with terrane corrections…	N / A
9. Mineralisation: Usually abundant or indicative of deeply penetrating fracture systems…	Riolago (HZ)
10. Earthquake epicentres / volcanic centres and intrusions…	N / A
11. Course changes of major streams/deflections of drainage systems/water and/or wind gaps…	N / A
12. Long Landsat photolineaments/Unusually dense air photo lineaments…	N / A
13. Facies and thickness changes of stratigraphical units…	Genestosa Fault (HZ)
14. Blocky shapes on isopach maps, including abrupt thickness changes across straight lines…	N / A
15. Springs: unusual temperatures, chemistries and/or yields…	Genestosa Fault (HZ)
16. Gas or oil seeps / High or low yields of water or gas wells…	N / A
17. Recess / salient production (Irregularly shaped, rifted continental margins)…	Hinge Zone
18. Localised thrust-sheet rotations (vertical-axis rotations)…	Hinge Zone
19. Along-strike variations in structural style (e.g., thick- / thin-skinned deformation) / lateral shortening / buttressing effects (e.g., duplex / antiformal stack formation)…	Hinge & Southern Zone
20. Along-strike variations in degree of reactivation or pre-existing structures (e.g., inversion)…	Cueto Negra-Brañillín Window

Table 6.1: Transverse zone identification criteria used in previous global research (Adapted after Wheeler, 1980). Evidence for classification as a transverse zone provided (HZ = Hinge Zone).

6.4.2. Role of the Pre-thrust template

The role of the pre-thrust template for the formation of potential transverse zones / cross-strike discontinuities within the Cantabria-Asturian Arc is difficult to determine as more than one phase of thrusting has occurred. Structural events within the Cantabria-Asturian Arc have been restored by numerous authors to determine Variscan age locations of thrusts (e.g., Kollmeier *et al*., 2000; Keller *et al*., 2008). However, few studies have been undertaken to determine the characteristics and structure of the pre-Variscan passive margin. As such, the role of the pre-thrust template for the production of suggested cross-strike discontinuities / transverse zones remains unconstrained. Observations within this research highlight a dominance of inversion along pre-existing extension faults within the Cantabria-Asturian Arc, particularly within the southern domain (e.g., Cueto Negra-Brañillín Window). However, the degree to which inversion alone results in cross-strike discontinuity formation within the Cantabria-Asturian Arc is hard to quantify.

On a regional scale, along-strike stratigraphical thickness variations are identified, particularly within Ordovician to Devonian strata from the southern arm of the Cantabria-Asturian Arc into the northern domain. A distinct increase in thrust sheet thickness is also observed, with only a few thrusts developing northwards from the transition hinge domain producing thrust sheets up to 4.75 kilometres thick, in comparison to those within the southern arm which are rarely more than one and a half kilometres thick. This along-strike change in stratigraphical thicknesses would be more conducive for the production of fault-propagation and fault-bend folds rather than thrusting. Consequently a fold-dominant domain is identified within the northern domain, whilst a fold-thrust dominant domain is identified within the transition hinge and southern domains. This constitutes a displacement-transfer zone under the criteria of Dahlstrom (1969) within the Urria region north of the transition hinge domain (Figure 6.8; 6.10).

6.4.3. Role of thrust translation transport

This research identifies an along-strike change in thrust translation direction from north-northeast (010°) within the southern domain to a northeast (030°) transport across the transition hinge and into the northern domain of the Cantabria-Asturian Arc using a variety of geometrical and kinematic indicators. This transport variation within the northern regions of the transition hinge domain may account for the development of large-scale transpressional structures identified along the Genestosa Fault and small-scale transpressional structures identified within the Abelgas Valley. However, the development from an east-west compression phase within the Moscovian (Early Carboniferous) to a north-south compression during oroclinal bending within the Early Permian and the production of syn-kinematic structures such as the transition hinge conical fold is the dominant cause for the development of cross-strike and along-strike discontinuities within the Cantabria-Asturian Arc. This orthogonal change in transport direction results in the reactivation of thrusts within the southern arm of the Cantabria-Asturian Arc, truncating pre-existing structures and creating along-strike structural disparities. Furthermore, later deformation events, such as the Alpidic Orogeny, may have also extenuated structural disparities.

6.5. Summary

Investigatory regional-scale studies within the Somiedo-Correcillas Unit of the Cantabria-Asturian Arc highlight a series of disparities along-strike on a variety of scales. A fold-dominant northern zone comprising thick stratigraphical successions is identified within map-view. Fault network analyses highlight that this northern zone comprises only a few laterally continuous, eastward-vergent, thrusts spaced up to 4.75 kilometres apart, along which fault-bend and fault-propagation folds are developed. No cross-strike discontinuities are identified within the northern domain. Conversely, the southern arm of the Cantabria-

Asturian Arc comprises a fold-thrust dominant zone composed of numerous thrust which breach pre-existing fold sets, indicating a northwards transport direction. A series of transport aligned thrust ramps and thrust bifurcations highlight a potential cross-strike discontinuity, the Villamanín Transverse Structure. This structure is suggested to comprise a lateral ramp connecting a large frontal ramp to a series of smaller frontal ramps along-strike. Frontal structures are suggested to comprise inverted extensional faults, the intersections of which produce areas of buttressing and along-strike disparities along the Somiedo-Correcillas Sole Thrust.

These contrasting domains are separated by a transition hinge domain which is classified within this research as a transverse zone. Within this transverse zone a northern hinge dominated by transpressional deformation along a east-northeast to west-southwest orientated transverse fault (i.e., the Genestosa Fault) is identified. This fault compartmentalises a fold-dominant northern wall from a fold-thrust dominant southern wall. The southern hinge is dominated by evidence of reactivated thrusts which truncate pre-existing structures. The core of the hinge is dominated by the development of a large conical fold.

This research concludes that this transverse zone is produced by a multiphase development. Original eastward propagating thrusts developed during the Variscan Orogeny are deformed during oroclinal bending via vertical axial rotations within the Early Permian during a change to north-south compression. This development produces the conical fold within the core of the transition hinge domain. Continued deformation compartmentalises deformation within the northern and southern hinges against this conical fold. The northern hinge is laterally compressed between the Genestosa Fault and the northern limb of the conical fold producing transpressional structures, such as antiformal stacks and sidewall duplexes. Conversely, the southern hinge is reactivated during north-south compression, truncating structures produced during oroclinal bending. Similar reactivations are identified within the southern arm of the Cantabria-Asturian Arc producing large-scale inversion structures (i.e., the Cueto Negra-Brañillín Window over the Léon Fault). Reactivations and further tightening of structures during later deformation events, such as the Alpidic Orogeny, cannot be discounted and therefore a structural overprint may be established within the Cantabria-Asturian Arc.

The development of this transverse zone is therefore controlled by contrasting transport directions during multiphase orogenic events rather than by any one parental sub-décollement structure. It must therefore be considered that many potential transverse zones identified within the Cantabria-Asturian Arc are syn-kinematic in nature, as no guarantees can be determined as to whether structures are orientated over their original parental structures, with the notable exception of the Genestosa Fault.

Chapter Seven:

Transverse Zones in Thrust Belts: Discussion

In chapters four, five and six, a series of cross-strike discontinues / transverse zones have been identified. The potential development of these discontinuities and the role of the pre-thrust template and thrust translation (i.e., regional transport) in their formation have been discussed. This chapter summarises these discussions and places them into a wider context of global cross-strike discontinuity / transverse zone research. New methodologies developed within this research are also evaluated post-application within the Moine and Cantabrian thrust belts. The wider implications of this research within future applications are also discussed.

7.1. Introduction

This chapter places observations and discussions within chapters five and six into the context of global cross-strike discontinuity / transverse zone research. Findings observed within the Moine and Cantabrian thrust belts are examined to address the aims of this research. The objectives of this chapter are:

- To discuss the three-dimensional architecture of, and linkages across, cross-strike discontinuities / transverse zones to identify which types of structures are important for cross-strike discontinuity / transverse zone formation (i.e., pre-, syn-, and / or post-depositional / kinematic features) and what these linkages mean in terms of lateral changes (i.e., gradational versus abrupt variations),

- To discuss the effect and / or control the pre-thrust template exerts upon cross-strike discontinuity / transverse zone formation and thrust belt development. Within this objective the critical nature of the wavelength and / or amplitude of potential basement steps are discussed.

- To ascertain the role of thrust translation (i.e., regional transport), in relation to potential pre-existing transverse structures and the role transport plays in the development of cross-strike discontinuities / transverse zones,

- To evaluate new methodologies developed within this research, tested within the southern Appalachian Thrust Belt, Alabama, USA, and applied within the Moine and Cantabrian thrust belts for cross-strike discontinuity / transverse zone identifications.

7.2. Analysis of three-dimensional architectures of, and linkages across, cross-strike discontinuities / transverse zones

Thomas (1990) was the first to discuss the finer-scale anatomy of transverse zones, proposing that transverse zones were composed of 'lateral connectors' (later redefined as cross-strike linkages in Thomas & Bayona, 2002), a variety of which may be aligned orthogonal to regional strike forming thrust-belt discontinuities. Thomas (1990) defined the characteristics of three principal types of cross-strike linkage: (1) lateral ramps, (2) displacement transfer zones, and (3) transverse faults. Combinations of structural and stratigraphical variations, both internal and external to the allochthon including, sub-décollement basement faults, pre-thrusting deformation of cover strata above basement faults, and / or along-strike variations in mechanical stratigraphy were identified by Thomas (1990) as controlling cross-strike linkage alignments within transverse zones.

A series of transport-lateral and transport-parallel cross-sections and transport-lateral stratigraphical separation diagrams, assisted by geometrical observations during ground-truthing and 1:10,000-scale remapping, were constructed to determine the three-dimensional architecture and cross-strike linkages within the Moine and Cantabrian thrust belts. New thrust ramp identification methodologies and fault network analyses also allowed cross-strike linkages to be determined.

Three-dimensional architectures within the Loch Maree Transverse Zone highlight two contrasting developments within the southern and northern walls, separated by the Loch Maree Fault. Within the southern wall of the Loch Maree Transverse Zone (i.e., the Beinn Eighe Massif to Meall a’ Ghiubhais sectors), a series of imbricates, comprising Torridonian and Cambro-Ordovician strata within the footwall of the Kinlochewe Thrust, indicate the north-eastward development of the Achnashellach Culmination which bulged up the Kinlochewe Thrust Sheet and structurally higher thrusts. Thrust sequences highlight fold-thrust architectures, with oscillatory and out-of-sequence thrusting as a result of interactions with the pre-thrust template. Cross-strike linkages within this southern wall comprise a series of large- and small-scale lateral ramps (e.g., Beinn Eighe Lateral Ramp, Doire Dharaich and Leathad Buidhe transverse structures), along which structural disparities are identified.

Development of fold-thrust architectural sequences within the northern Achnashellach Culmination (i.e., the Loch Maree Transverse Zone southern wall) are comparable to culmination developments within other transverse zone settings including the Traligill and Oykel Bridge transverse zones, which compartmentalise the Assynt and Cassley culminations within the northern sections of the Moine Thrust Belt (Elliott & Johnson, 1980; Butler *et al.,* 2007; Krabbendam & Leslie, 2010; Leslie *et al.,* 2010). A further example of such developments is identified within the Canadian Rockies (e.g., the Limestone Mountain Culmination; Bégin & Spratt, 2002).

Conversely, the northern wall of the Loch Maree Transverse Zone (i.e., the Heights of Kinlochewe sector) is dominated by brittle thrust-dominant architectures which truncate pre-existing structures within the pre-thrust template. A sequence of right-way-up and completely overturned slabs of Torridonian sandstones and Lewisian gneisses, overlying a right-way-up Cambrian succession is subsequently produced. These observations contrast markedly with previous interpretations by Matthews (1984) and Butler *et al.,* (2007). Out-of-sequence and oscillatory thrusting is also observed within this northern wall. A series of cross-strike linkages comprising lateral ramps and later strike-slips faults are identified within the hinterland of the Heights of Kinlochewe northern wall within the Glen Bruachaig-Incheril Window (i.e., the Innes Dhriseach and Garbh Leathad transverse structures). However, unlike the southern wall, these lateral ramps are produced syn-kinematically, resulting in structural disparities during development of the Glen Bruachaig-Incheril Window.

A distinct architectural compartmentalisation is therefore evident across the Loch Maree Fault. The Loch Maree Fault therefore defines the edge of the Achnashellach Culmination within which the southern wall of the Loch Maree Transverse Zone comprises the north-eastwards tapering edge, supporting previous interpretations by Butler *et al.,* (2007). Only a few thrusts are laterally continuous between the southern and northern walls (i.e., the Coulin and Moine thrusts). It is therefore evident that the effects of cross-strike discontinuities within the Loch Maree Transverse Zone acutely effect early phases of deformation and diminish with time during the development of the thrust belt.

Within the Cantabrian Thrust Belt, a similar along-strike structural style change from fold-thrust dominant architectures within the southern domain of the Cantabria-Asturian Arc, to a fold-dominant architecture within the central to northern domain is identified supporting previous observations by Kollmeier *et al.,* (2000) and Bulnes & Aller (2002). This transition is accommodated via a transition hinge, which has been classified as a large-scale transverse zone within this research. Transition hinge comprises a large conical fold along which a distinct curvature of the Somiedo-Correcillas Sole Thrust is observed, and along which deformation has been compartmentalised.

Within the northern section of the transition hinge domain, a structure similar to the Loch Maree Fault is identified, the Genestosa Fault. Within the southern wall of this fault, a fold-thrust dominant sequence is identified, whilst within the northern wall, a fold-dominant sequence is observed. The development of such a structure has been suggested by Kollmeier *et al.,* (2000) to be linked to along-strike thickness variations within the pre-thrust template and along-strike changes in deformation style, observations which are supported within this research. Similar examples of transverse fault formation linked to thrust belt curvature are identified within the Canadian Rockies, south-western Alberta / south-eastern British Columbia, along the St. Mary and Moyie faults (e.g., Benvenuto & Price, 1979).

North of the Genestosa Fault, a series of fault-bend and fault-propagation folds are identified within the Urria region. These folds comprise the third and final type of cross-strike linkage, a displacement-transfer zone, which connects the two along-strike structural variations. Similar examples to this structure are identified within the Anniston and Bessemer transverse zones (e.g., Pell City Thrust Sheet and 'The Knot'; Apotria, 1995; Allerton, 1998; Wilkerson *et al.,* 1991; 2002; Thomas & Bayona, 2002).

Within the Loch Maree Transverse Zone, fault network and thrust ramps analyses identify that lateral ramps and compartmentalisations along transverse faults dominate the three-dimensional architecture within this study area. Similarly, within the Cantabrian Thrust Belt the architecture is dominated by a combination of lateral ramps, transverse faults and one displacement transfer zone. However, observations within the Cantabrian Thrust Belt indicate that the development of cross-strike discontinuities / transverse zones is prevalently linked to the evolution of the thrust belt as a whole.

Thomas (1990) and Brewer (2004) identified that the development of cross-strike linkages, and therefore subsequent cross-strike discontinuity / transverse zone architecture, is directly linked to local geological characteristics. This research supports these observations and suggests that the predominant controlling factors which determine cross-strike discontinuity / transverse zone architecture and cross-strike linkages are found within the development of the pre-thrust template and the subsequent orientation of the deformation front against this template (i.e., the role of regional transport).

7.3. Analysis and evaluation of the role of the pre-thrust template in the development of cross-strike discontinuities / transverse zones

The pre-thrust template within the Loch Maree Transverse Zone, and on a larger-scale the Somiedo-Correcillas Unit within the Cantabrian Thrust Belt, has a major impact on the production of cross-strike discontinuities and cross-strike linkages within the developing thrust belts. Discontinuities produced during pre-thrust template development determine what structures are presented to the propagating thrust front and in turn, determine what syn-kinematic discontinuities are produced. Severity of pre-thrust template discontinuities will also impact on the amplification of such features into higher thrust sheets as the thrust belt develops further.

Within the Loch Maree Transverse Zone southern wall, post-depositional fault movements within the Beinn Eighe Massif Fault cause a drastic north-eastwards reduction in the amount of available Torridonian sandstones presented to the thrust front during the production of individual fault blocks. Transport-transverse structures within the pre-thrust template, such as the Leathad Buidhe and Doire Dharaich transverse structures compartmentalise forelandward deformation, encouraging a north-eastwards rise of the Sole Thrust via a series of small steps within the pre-thrust template. These structures produce pre-thrust folds as lithologies interact with pre-thrust irregularities and the advancing thrust front.

Conversely, within the Loch Maree Transverse Zone northern wall pre-, and post depositional movements along the Loch Maree Fault cause a dramatic drop in the relative thrust translation depth along-strike; whilst the presence of large pre-thrust folds greatly affect resultant structures. Development of lateral ramps are prevalent within the northern wall (i.e., Creag Ruadh, Innis Dhriseach and Garbh Leathad), whilst pre-thrust template fold structures are either incorporated or truncated by the advancing thrust front. Large pre-thrust folds emplace comparably incompetent lithologies together, producing individual compartments along-strike as lithologies interact with the propagating thrust front. Interactions produce syn-kinematic cross-strike discontinuities, further complicating the cross-strike map-view expression within the Glen Bruachaig-Incheril Window. Later strike-slip movements along the Loch Maree Fault and structures such as the Ath na Sealga Fault further enhance map-view structural disparities.

The role of the pre-thrust template for the formation of potential transverse zones / cross-strike discontinuities within the Somiedo-Correcillas Unit, Cantabrian Thrust Belt, is difficult to determine for several reasons. Firstly, more than one phase of thrusting has occurred in orthogonal directions removing elements of the pre-thrust template. Furthermore, few studies have been undertaken to determine the characteristics and structure of the pre-Variscan passive margin. As such, the role of the pre-thrust template for the production of suggested cross-strike discontinuities / transverse zones remains unconstrained. However, observations within this research highlight a dominance of inversion within the Cantabrian Thrust Belt, particularly within the southern domain along major structures such as the Léon Fault (e.g., Cueto Negra-Brañillín Window) indicating a strong link between pre-thrust architecture and subsequent reactivations.

Stratigraphical thickness variations are identified within regional-scale observations particularly within Ordovician to Devonian strata from the southern arm of the Cantabria-Asturian Arc into the northern domain. A distinct increase in thrust sheet thickness is also observed, with only a few thrusts developing northwards from the transition hinge domain producing thrust sheets up to four and three quarter kilometres thick, in comparison to those within the southern arm which are rarely more than one and a half kilometres thick. The development of this along-strike change in stratigraphical thickness focused north of the Genestosa Fault within the transition hinge domain produces a displacement transfer zone within the Urria region comprising a series of fault-bend and fault-propagation folds. The development of this structure separates the fold-dominant domain identified within the northern domain, from a fold-thrust dominant domain identified within the transition hinge and southern domains and may have focused deformation within the transition hinge domain during its development.

It is therefore evident that the pre-thrust template plays a crucial role in the evolution of the advancing thrust front architectural development and subsequent syn-kinematic development of structures. It is therefore critical to address the following questions;

- Which types of pre-existing structure are important for cross-strike discontinuity / transverse zone formation (i.e., pre-, syn-, and / or post depositional)?
- How critical is the wavelength and / or amplitude of potential steps within the pre-thrust template (i.e., gradational versus abrupt variations)?
- How they affect or control the thrust system as a whole?

Within the Loch Maree Transverse Zone, abrupt compartmentalisation either side of the Loch Maree Fault developed during pre-, and post-depositional fault movements control the separate kinematic developments within the northern and southern walls of the Loch Maree Fault, resulting in the incorporation of basement lithologies within the northern wall. Cross-strike discontinuities identified across the Loch Maree Fault are comparable with those within the Charleston Transverse Zone, South Provo Salient, Utah (e.g., Paulsen & Marshak, 1998) and the Ballabio-Barzio Transverse Zone, Southern Alps, northern Italy (Laubscher, 1985; Schönborn, 1990; 1992). Further abrupt variations are identified across the Beinn Eighe Lateral Ramp.

This research shows that relatively small disturbances within the pre-thrusting template can lead to significant lateral variations in thrust geometry, especially along long-lived structures such as the Loch Maree Fault, and its related Proterozoic shear zone. Observations within the Loch Maree Transverse Zone are indicative of transverse zones within other regions of the Moine Thrust Belt where cross-strike discontinuities / transverse zones are developed over long-lived structures within the basement (i.e., a long-lived, ductile, sub-décollement Palaeozoic shear zone). Similar observations to those identified along the Loch Maree Fault are observed within the northern Moine Thrust Belt within the Oykel Bridge and Traligill transverse zones which developed over the Stoer and Canisp shear zones (Krabbendam & Leslie, 2010; Leslie *et al.,* 2010). Further examples are also identified within the Montana Transverse Zone, Canadian Rockies (e.g., Ross *et al.,* 1991; McMechan, 2002; Bégin & Spratt, 2002; Pană, 2003). It is therefore indicative that structural disparities along-strike within the Moine Thrust Belt are commonly greater than their original parental structure, although this is not indicative of all transverse zones.

Where abrupt variations in pre-thrust template architecture are observed, greater cross-strike discontinuities are identified, commonly along transverse faults. Furthermore, alternations along-strike between thicker and thinner stratigraphical successions within the pre-thrust template promotes cross-strike discontinuity development (Pohn, 1998; Bigi *et al.,* 2009). Cross-strike discontinuities observed within the Cantabrian Thrust Belt across the Genestosa Fault, resulting from abrupt stratigraphical thickness variations, are a good example of this. Within the Cantabrian Thrust Belt, along-strike variations in stratigraphical thickness are assisted by laterally discontinuous stratigraphical units, structural highs and along-strike differential developments of extension faults. Further transverse zones highlighting abrupt variations resulting from along-strike stratigraphical thickness variations are identified within the central Fars region, Iran (e.g., Motamedi *et al.,* 2012).

Conversely, where minor steps are identified (i.e., Doire Dharaich and Leathad Buidhe) or where gradational changes of stratigraphy are observed within fault network and cross-section analyses, small deflections are identified and thrusts preferentially branch along a series of branch-lines rather than develop compartmental transverse faults. These observations support those of Liu *et al.,* (1992) and Turner *et al.,* (2010) within the Keping Shan Thrust Belt.

7.4. Analysis and evaluation of the role of thrust translation (i.e., regional transport) in relation to potential pre-existing transverse structures and cross-strike discontinuity / transverse zone development

The significance of thrust transport direction on the formation of cross-strike discontinuities is highly dependent upon the orientation of structures identified within the pre-thrust template and the development of syn-kinematic structures during thrust translation. In comparison to other thrust belts, such as the Cantabrian Thrust Belt, thrust translation directions are uniform along the length of the Moine Thrust Belt. As such, localised cross-strike discontinues are transported along their parent structure. Localised obliquities would still be translated along their parent structures but at oblique angles to their parent structure (Wheeler, 1986; Thomas, 1990). As such, cross-strike discontinuities / transverse zones are easier to identify.

Conversely, structures within the Cantabrian Thrust Belt highlight a multiphase development formed during more than one orogenic phase and / or event (i.e., Variscan and later Alpidic orogenic events). Therefore, these structures would be translated a long distance from parental structures unless they were developed during the last deformation phase (Frizon de Lamotte & Guezou, 1995; Marshak, 1998, Cook, 2010). However, these structures would still be syn-kinematic in nature, produced as a result of multiple translations. As such only potential cross-strike discontinuities / transverse zones are identified. Kinematic indicators identified during ground-truthing and / or remapping within the Moine and Cantabrian thrust belts in unison with new fault network analyses allowed thrust translation orientations and thrust ramp classifications to be determined to identify transport-transverse structures.

Within the Loch Maree Transverse Zone northern and southern walls, transpressional structures are identified linked to along-strike responses to the regional (290 / 300°) transport direction and the pre-thrust template. Lateral shortening of thick imbricate slices within the southern wall are observed along interaction points with pre-thrust template structures, most notable along the Leathad Buidhe and Doire Dharaich Transverse System within the Meall a' Ghuibhas hillside. Drastic architectural differences are not observed within the Loch Maree Transverse Zone southern wall as sub-décollement structures are aligned sub-parallel to the regional (290 / 300°) transport direction. However, minor thrust translation deflections are noted across thrusts within the Beinn Eighe Massif as a result of cross-strike interactions between thick and much thinner Torridonian sandstone sequences across the Beinn Eighe Lateral Ramp.

However, within the Loch Maree Transverse Zone northern wall a far more evident transpressional overprint is identified. Thrust translation within the northern wall is slightly oblique (10 to 20°) to the strike of the Loch Maree Fault (LMF) at 310°. This cross-strike difference in alignment of pre-thrust template structures would have assisted the production of cross-strike discontinuities, such as the Creag Ruadh lateral ramp against the Proterozoic shear zone located beneath the Loch Maree Fault, and the formation of the Glen Bruachaig-Incheril Window beneath the Heights of Kinlochewe Thrust Sheet.

Development of the Glen Bruachaig-Incheril Window and its internal syn-kinematic structures, which highlight cross-strike structural disparities, are comparable to structures identified within the Rising Fawn and Anniston transverse zones which develop within the trailing edge of the Pell City Fault and the Jacksonville Fault within the Pell City-Jacksonville thrust system as a result of compartmentalisation produced during development (e.g., the Ballplay, Jacksonville and Fort McClellan Windows; Rich, 1992; Thomas, 2001; Thomas & Bayona, 2002; 2005). Obliquity would have also assisted bulging of the Loch Maree Transverse Zone northern wall thrust systems, causing along-strike down-cutting of the Meallan Ghobhar Thrust into the Coire Each Thrust and enhance the prospect of forelandward, transport-sub-parallel, out-of-sequence thrusting.

Similarly, this research identifies an along-strike change in thrust translation direction from north-northeast (010°) within the southern domain to a northeast (030°) transport across the transition hinge and into the northern domain of the Cantabrian Thrust Belt using a variety of geometrical and kinematic indicators. This transport variation within the northern regions of the transition hinge domain would account for the development of large-scale transpressional structures identified along the Genestosa Fault including the Torre de Babia antiformal stack, the Robledo-Cospedal sidewall duplex, and the La Majúa duplex. A similar structure to the Robledo-Cospedal sidewall duplex is identified within the Angel Fault System within the Anniston Transverse Zone (Thomas, pers. comms. 2011). Further small-scale transpressional structures are identified within the Abelgas Valley.

However, the development from an east-west compression phase within the Moscovian (Early Carboniferous) to a north-south compression during oroclinal bending and vertical-axial rotations within the Early Permian is the dominant cause for the development of cross-strike and along-strike discontinuities within the Cantabrian Thrust Belt. Syn-kinematic structures, such as the transition hinge conical fold developed within the Bodon Unit, are produced during this deformation phase resulting in compartmentalisation within its northern and southern limbs during continued translation. This orthogonal change in transport direction results in the reactivation of thrusts within the southern arm of the Cantabria-Asturian Arc, truncating pre-existing structures and creating along-strike structural disparities (e.g., the 'bevelled zone'). Major structures, such as the Léon Fault, are also reactivated producing dominant frontal structures (i.e., the Cueto Negra-Brañillín Window).

Transpressional structures within the northern hinge would have also been tightened and further enhanced during a north-south compression phase during the development of thrust fault curvature along the Somiedo-Correcillas Thrust and interactions within the central conical fold (e.g., Apotria, 1990; Schönborn, 1992; Dewey *et al.,* 1998). Later deformation events, such as the Alpidic Orogeny, may have also extenuated structural disparities during further reactivations during north-south compression. As such, the identification of potential cross-strike discontinuities / transverse zones within oroclinal or multiphase deformation settings is far more complex than within linear fold-thrust belts. However, identifications of structures such as the Aralla Lineament have been ascertained and verified supporting the observations of Nijman & Savage (1989). A new interpretation for the development of this lineament is provided, classifying it as a transverse zone developed during oroclinal bending.

7.5. Evaluation of new cross-strike discontinuity / transverse zone identification techniques

Techniques utilised for determining along-strike architectural variations are commonly implemented over a variety of scales to good effect. Techniques such as stratigraphical separation diagrams, geological map analyses and / or re-mapping, cross-section construction and collection of geometrical and / or kinematic data sets form a prerequisite cornerstone within cross-strike discontinuity research studies globally. However, within architectural analyses of cross-strike discontinuities, localised detailed field studies commonly focus on individual structural development of faults and folds, or specific regions or structures, and therefore commonly overlook relationships between regional and localised structural developments and vice versa. Few studies have developed and implemented techniques which can be utilised within any fold-thrust belt to identify thrust ramps and cross-strike discontinuities from a regional- to localised-scale and to the thrust belt as a whole. Furthermore, spatial distribution analyses of architectural components, such as branch-lines, fault-tip lines and fault cut-off points, have not been widely implement within cross-strike discontinuity studies.

New cross-strike discontinuity identification methodologies have been developed to identify transverse zones on regional and localised spatial scales within this research. These methods include fault network analyses incorporating:

- Thrust ramp colour coding classifications
- Branch-line analyses
- Fault-tip line analyses
- Cut-off point analyses

Regional analyses of the interplay of different structural components within thrust systems, (i.e., the fault network) have been utilised within this research to analyse along-strike compartmentalisation and terminations of structures within transverse zones and the thrust belt as a whole, including along-strike variations in structural style (e.g., folding versus faulting-dominant domains) along-strike identifications of thrust ramps (which in turn are classified dependant on alignment with regard to regional thrust translation), and determination of spatial distributions and architectural components of cross-strike discontinuities and cross-strike linkages. Branch-line, fault-tip line and cut-off point analyses determine thrust nucleation, propagation, termination and stratigraphical décollement relationships along-strike plus cross-strike linkages within transverse zones.

Within the Moine Thrust Belt, the application of this methodology identified transport-aligned thrust ramps allowing potential transverse structures to be identified. These included the Beinn Eighe Lateral Ramp, the Doire Dharaich, and Leathad Buidhe transverse structures within the Loch Maree Transverse Zone southern wall. Further potential transverse structures were identified within the Loch Maree Transverse Zone northern wall including the Creag Ruadh Sidewall, the Innis Dhriseach transverse structure and the Garbh Leathad transverse structure. Thrust ramp alignments also identified areas of out-of-sequence or oscillatory thrusting when combined with geometrical and kinematic data collection. Branch-line, fault-tip line and cut-off point analyses identified areas where potential small steps where located within the Loch Maree Transverse Zone southern wall accommodating a north-eastward rise in the Sole Thrust.

Within the Cantabrian Thrust Belt, transport-aligned thrust ramps were also identified. However, unlike the Moine Thrust Zone where a uniform transport direction was observed, a multiphase development occurs within the Cantabrian Thrust Belt as a result of oroclinal development. Therefore, thrust ramp alignments were determined to be syn-kinematic identifying only the last phase of deformation within the Cantabrian Thrust Belt and may not be indicative of parental sub-décollement structures. This methodology did however identify a potential syn-kinematic structure within the Villamanín region (i.e., the Villamanín Lateral Ramp) through a combination of aligned thrust ramps, branch-lines and fault-tip lines.

Although this methodology was a success in identifying transport-aligned thrust ramps and thrust nucleation, propagation and termination zones, correlations with geometrical and kinematic data during ground truthing are required for validation. Furthermore, this method does not identify all potential transverse structures within every geological setting. Therefore further refinements are needed through applications within more fold-thrust belt settings to bridge the gap between a linear and oroclinal fold-thrust setting. Further limitations within this methodology are dependent on the quality of original mapping data, along-strike continuations of thrusts for thrust ramp alignment studies and collection of geometrical and kinematic data (e.g., limited by vegetation cover within the Cantabrian Thrust Belt northern domain). This methodology adds weight to previous techniques used for cross-strike discontinuity / transverse zone identifications, particularly stratigraphical separation diagrams. Thrust facing analyses within this methodology also alleviate problems identified within Kwon & Mitra (2012) for identifying lateral ramps and displacement-transfer zones along-strike.

Development of this new cross-strike discontinuity identification technique allows greater understanding of how inherited and / or pre-thrust structures and their impacts on the sediment pile combine to influence the partitioning of the fold-thrust belt. This understanding has important implications for hydrocarbon exploration within foreland settings and current exploration within producing fold-thrust belts settings (e.g., Zagros and Appalachian fold-thrust belts). Partitions within hydrocarbon systems impact hydrocarbon exploration strategies, fluid migration pathways and hydrocarbon trapping capacities (e.g., Bégin & Spratt, 2002; Yassaghi & Madanipour, 2008; Pashin *et al.,* 2010; Aschoff *et al.,* 2011; Burberry *et al.,* 2011; Motamedi *et al.,* 2012).

7.6. Summary

Within the Moine and Cantabrian thrust belts, a combination of structural and stratigraphical variations, both internal and external to the allochthon including, sub-décollement basement faults, pre-thrusting deformation of cover strata above basement faults, and along-strike variations in mechanical stratigraphy control alignments of cross-strike linkages, determine subsequent thrust architectures and focus the development of cross-strike discontinuity / transverse zone development.

Lateral variations in thrust architecture along the length of the Moine Thrust Belt are strongly influenced by the existence of Proterozoic shear zones, and the brittle faults that commonly developed along these shear zones within the pre-thrust template (i.e., the Loch Maree Fault). These shear or fault zones trend west-northwest to east-northeast or northwest to southeast, and were thus aligned at small angles (10 to 20°) to the thrust transport direction (towards 290 / 300°). Therefore, cross-strike discontinuities are projected along the length of originating parental structures. The formation of the Loch Maree Transverse Zone is controlled by a series of abrupt pre-thrust template discontinuities which are exacerbated by the later development of the Achnashellach Culmination and transpressional deformation within the Heights of Kinlochewe northern wall resulting in the development of syn-kinematic cross-strike discontinuities. Amplifications of discontinuities diminish with time during orogenic development.

Conversely, the development of potential cross-strike discontinuities within the Cantabrian Thrust Belt is hard to determine due to multiple orogenic phases in orthogonal transport orientations. Extension faults identified within the study area are reactivated and / or truncated by later compressional events creating along-strike and cross-strike structural discontinuities. The role of transport within the Cantabrian Thrust Belt controls the development of potential cross-strike discontinuities during oroclinal development producing a series of syn-kinematic discontinuities, such as conical folds, which compartmentalise deformation further. Potential cross-strike discontinuities are therefore far travelled and unlikely to be near their originating parental structure.

This research therefore suggests that the formation of cross-strike discontinuities / transverse zones globally is predominantly controlled by the original architecture of the pre-thrust template and the orientation of transport against this template during subsequent orogenic deformation. However, this research further suggests that once one phase of deformation has occurred, any variation in subsequent deformation phases will destroy primary cross-strike discontinuities and produce new syn-kinematic structural discontinuities which only record the last phase of deformation of the last deformation event. These structures may not be rooted or focused along sub-décollement structures unless transport direction permits and / or the amplitude of the structure are large enough to continue compartmentalisation. Identifications of cross-strike discontinuities using new methodologies developed within this research assist previously applied methodologies but require further refinements for applications within various fold-thrust settings beyond the Moine, Cantabrian and Appalachian thrust belts.

Chapter Eight:

Conclusions and Future Work

Chapter eight provides conclusions based on the results of this research. Of particular importance is how this work augments our understanding of cross-strike discontinuity / transverse zone development spatially and temporally, and how this work provides a greater understanding of the controls within thrust systems within different orogenic settings. Broader implications for this research are discussed and potential future avenues of research are identified.

8.1. Introduction

The overall aim of this research was three-fold: (1) to determine the three-dimensional architecture of, and linkages across, cross-strike discontinuities / transverse zones; (2) to determine the role of thrust translation (i.e., regional transport), in relation to potential pre-existing transverse structures. This aim was expanded to also incorporate cross-strike discontinuities produced during alternating thrust translation directions and (3) to determine the effect and / or control the pre-thrust template exerts upon cross-strike discontinuities / transverse zone formation.

Two study areas were selected within well-understood and comprehensively mapped thrust belts, to demonstrate the application of new thrust ramp identification techniques developed within this research. These are implemented to identify and analyse cross-strike discontinuities / transverse zones. The two case study areas are located within the:

- Northern Achnashellach Culmination, Kinlochewe region along the Loch Maree Fault, Moine Thrust Belt, Northwest Highlands, Scotland

- Somiedo-Correcillas Unit, Cantabrian Thrust Belt (Cantabria-Asturian Arc), northern Spain, with particular focus within the San Emiliano region.

Techniques such as stratigraphical separation diagrams, geological map analyses and / or re-mapping, cross-section construction and collection of geometrical and kinematic data sets form a prerequisite cornerstone within cross-strike discontinuity research studies globally and are implemented within this research. New cross-strike discontinuity identification methodologies have also been developed to identify cross-strike discontinuities / transverse zones on regional and localised spatial scales within this research. These methods include fault network analyses incorporating:

- Thrust ramp colour coding classifications
- Branch-line analyses
- Fault-tip line analyses
- Cut-off point analyses

Regional analyses of the interplay of different structural components within thrust systems, (i.e., the fault network) have been utilised within this research to analyse along-strike compartmentalisation and terminations of structures within transverse zones and the thrust belt as a whole, including along-strike variations in structural style (e.g., folding versus faulting-dominant domains), along-strike identifications of thrust ramps (which in turn are classified defendant on alignment with regard to regional thrust translation), and determination of spatial distributions and architectural components of cross-strike discontinuities and cross-strike linkages. Branch-line, fault-tip line and cut-off point analyses determine thrust nucleation, propagation, termination and stratigraphical décollement relationships along-strike plus cross-strike linkages within transverse zones.

The following sections summarise the results of this research and place them into the context of the aims identified within Chapter One (section 1.2). Future avenues of research are subsequently discussed.

8.2. Results: Loch Maree Transverse Zone (LMTZ), Kinlochewe region, northern Achnashellach Culmination, Moine Thrust Belt, Northwest Highlands, Scotland

Within the Kinlochewe district where the Loch Maree Fault (LMF) transects the Moine Thrust Belt, a pronounced lateral change in thrust architecture is identified defining the Loch Maree Transverse Zone (LMTZ). Within the Loch Maree Transverse Zone northern wall a thrust dominated region of right-way-up and completely overturned slabs of Torridonian sandstones and Lewisian gneisses, overlying a right-way-up Cambrian succession is clearly identified. This architecture is in sharp contrast to classically imbricated repetitions of Torridonian-Cambrian rocks within the southern wall of the Loch Maree Fault. This section identifies a two hundred metre ‘thin flap’ of Eriboll Formation quartzites to the southeast of the Meall a’ Ghiubhais Klippe developing south-westwards into much thicker one and a half kilometre ‘slab-like ’Torridonian sandstone and Eriboll Formation imbricate slices that can be traced farther south within the Achnashellach Culmination. Oscillatory and out-of-sequence phases of thrusting are observed within both the northern and southern walls.

A distinct compartmentalisation of the Moine Thrust Belt architecture is therefore apparent across the Loch Maree Fault which is far more complex than previously suggested by previous authors (e.g., Matthews, 1984; Butler *et al*., 2007). Compartmentalisation is suggested to be a response to a significant offset of the pre-thrust template that generated a transport-parallel lateral ramp or sidewall during thrust translation (i.e., Creag Ruadh lateral ramp), aligned sub-parallel to a Proterozoic shear zone. Further transport-transverse structures highlighting pre-, syn-, and post-thrusting cross-strike discontinues are identified within the northern and southern walls using new thrust ramp architectural analyses and transport-lateral and transport-parallel cross-sections (i.e., the Leathad Buidhe, Doire Dharaich, Innis Dharaich and Garbh Leathad transverse structures). A new pre-thrust template highlighting these structures is presented within this research.

The Loch Maree Transverse Zone (LMTZ) therefore marks the southward change from a thrust-dominant northern Moine Thrust Belt, to the fold-and-thrust architecture identified within the southern Moine Thrust Belt, which is bulged by the still younger Achnashellach Culmination. This demonstrates a return to foreland-propagating thrusting in the later stages of development of the Moine Thrust Belt south of the Loch Maree Transverse Zone. The (brittle) Moine Thrust then truncated all of the structural elements beneath, indicating a final hinterland-propagating episode of movement all along the Moine Thrust Belt suggesting that the influence of the Loch Maree Transverse Zone, and comparable transverse zones within the Moine Thrust Belt diminished in time as the thrust belt evolved. This research shows that relatively small disturbances within the pre-thrusting template can lead to significant lateral variations in thrust geometry, especially along long-lived structures such as the Loch Maree Fault, and its related Proterozoic shear zone.

8.3. Results: Somiedo-Correcillas Unit, Cantabrian Thrust Belt (Cantabria-Asturian Arc), northern Spain, with particular focus within the San Emiliano region

Investigatory regional-scale studies within the Somiedo-Correcillas Unit of the Cantabria-Asturian Arc highlight a series of disparities along-strike on a variety of scales. A fold-dominant northern zone comprising thick stratigraphical successions is identified within map-view. Fault network analyses highlight that this northern zone comprises only a few laterally continuous, eastward-vergent, thrusts spaced up to four and three quarter kilometres apart, along which fault-bend and fault-propagation folds are developed. No cross-strike discontinuities are identified within the northern domain. Conversely, the southern arm of the Cantabria-Asturian Arc comprises a fold-thrust dominant zone composed of numerous thrusts which breach pre-existing fold sets, indicating a northwards transport direction. A series of transport aligned thrust ramps and thrust bifurcations highlight a potential cross-strike discontinuity, the Villamanín Transverse Structure. This structure is suggested to comprise a lateral ramp connecting a large frontal ramp to a series of smaller frontal ramps along-strike. Frontal structures are suggested to comprise inverted extensional faults, the intersections of which produce areas of buttressing and along-strike disparities along the Somiedo-Correcillas Sole Thrust.

These contrasting domains are separated by a transition hinge domain which is classified within this research as a transverse zone. Previous authors (e.g., Nijman & Savage, 1989) suggest that this transition hinge was the location of a sub-décollement structure which compartmentalised deformation (i.e., the Aralla Lineament). Within this transverse zone a northern hinge dominated by transpressional deformation along a east-northeast to west-southwest orientated transverse fault (i.e., the Genestosa Fault) is identified. This fault compartmentalises a fold-dominant northern wall from a fold-thrust dominant southern wall. The southern hinge is dominated by evidence of reactivated thrusts which truncate pre-existing structures. The core of the hinge is dominated by the development of a large conical fold.

This research concludes that this transverse zone is produced by a multiphase development. Original eastward propagating thrusts developed during the Variscan

Orogeny are deformed during oroclinal bending via vertical axial rotations within the Early Permian during a change to north-south compression. This development produces the conical fold within the core of the transition hinge domain. Continued deformation compartmentalises deformation within the northern and southern hinges against this conical fold. The northern hinge is laterally compressed between the Genestosa Fault and the northern limb of the conical fold producing transpressional structures including antiformal stacks (i.e., Torre de Babia antiformal stack) and sidewall duplexes (i.e., Robledo-Cospedal thrust splays). Conversely, the southern hinge is reactivated during north-south compression, truncating structures produced during oroclinal bending. Similar reactivations are identified within the southern arm of the Cantabria-Asturian Arc producing large-scale inversion structures (i.e., the Cueto Negra-Brañillín Window over the Léon Fault). Reactivations and further tightening of structures during later deformation events, such as the Alpidic Orogeny, cannot be discounted and therefore a structural overprint may be established within the Cantabria-Asturian Arc.

The development of this transverse zone is therefore controlled by contrasting transport directions during multiphase orogenic events rather than by any one parental sub-décollement structure. It must therefore be considered that many potential transverse zones identified within the Cantabria-Asturian Arc are syn-kinematic in nature, as no guarantees can be determined as to whether structures are orientated over their original parental structures, with the notable exception of the Genestosa Fault.

8.4. Outcome of research aims and objectives

This research has identified a series of cross-strike discontinues / transverse zones within the Moine and Cantabrian thrust belts. Results summarised above are placed within the context of the aims identified within Chapter One and global cross-strike discontinuity / transverse zone research. A brief discussion of the findings to each objective posed is provided.

Aim 1: To determine the detailed three-dimensional architecture of, and linkages across, cross-strike discontinuities / transverse zones

A new thrust ramp identification framework incorporating fault network analyses and stratigraphical separation diagrams to determine regional and localised spatial distributions of transversal structures was developed. This new technique was assisted by a spectrum of detailed thrust architectural and geometrical observations collected during detailed remapping or ground-truthing and a suite of high resolution transport-parallel and transport-lateral cross-sections to identify how thrust units and thrusts link together and relate to each other, and what these linkages mean in terms of lateral changes (i.e., gradational versus abrupt variations).

Within the Moine Thrust Belt, cross-strike linkages across the Loch Maree Transverse Zone were dominated by the production of lateral ramps along a pre-existing transverse fault, the Loch Maree Fault. These structures separated a fold-thrust dominant southern wall which was bulged up during the development of the Achnashellach Culmination, from a northern wall dominated by brittle, thrust dominant architectures. Conversely, within the Cantabrian Thrust Belt a large-scale transition from a fold-dominant northern domain to a fold-thrust southern domain via a transition hinge domain is identified. The development of this transition hinge domain occurred during oroclinal bending during the Early Permian forming a conical fold which compartmentalised deformation further. A series of cross-strike linkages are identified including lateral ramps, transverse fault and a single displacement-transfer zone. However, these structures indicate the last phase of deformation within the Cantabrian Thrust Belt and as such are not primary cross-strike linkages, with the notable exception of the Genestosa Fault.

Observations support previous authors interpretations (i.e., Thomas, 1990; Brewer, 2004) which suggests that the predominant controlling factors which determine cross-strike discontinuity / transverse zone architecture and cross-strike linkages within all transverse zones globally are found within the development of the pre-thrust template and the subsequent orientation of the deformation front against this template (i.e., the role of regional transport). However, this research builds on these interpretations suggesting that once one phase of deformation has occurred, any variation in subsequent deformation phases will destroy primary cross-strike discontinuities and produce new syn-kinematic structural discontinuities which only record the last phase of deformation of the last deformation event. These structures may not be rooted or focused along sub-décollement structures but focused along intersections of structures produced during different phases of deformation.

Aim 2: To determine the role of thrust translation (i.e., regional transport), in relation to potential pre-exiting transverse structures and / or the role of transport in the formation of cross-strike discontinuities / transverse zones

The significance of thrust transport direction on the formation of cross-strike discontinuities is highly dependent upon the orientation of structures identified within the pre-thrust template and the development of syn-kinematic structures during thrust translation. Kinematic indicators identified during ground-truthing and / or remapping within the Moine and Cantabrian thrust belts in unison with new fault network analyses allowed thrust translation orientations and thrust ramp classifications to be determined to identify transport-transverse structures.

Where transport was observed to be slightly oblique to pre-existing structures within the Moine and Cantabrian thrust belts (i.e., the Loch Maree and Genestosa faults) large transpressional structures were identified. Within the Loch Maree Transverse Zone northern wall these included the production of large folds prior to thrusting. Development of the pre-thrust transpressional folds exacerbated disparities within the northern wall of the Loch Maree Fault during thrusting, resulting in the production of sidewall lateral ramps such as the Creag Ruadh Lateral Ramp against the Proterozoic shear zone located beneath the Loch Maree Fault, and the formation of the Glen Bruachaig-Incheril Window beneath the Heights of Kinlochewe Thrust Sheet. Obliquity would have also assisted bulging of the Loch Maree Transverse Zone northern wall thrust systems, causing along-strike down-cutting of the Meallan Ghobhar Thrust into the Coire Each Thrust and enhance the prospect of forelandward, transport-sub-parallel, out-of-sequence thrusting.

Similarly, this research identifies an along-strike change in thrust translation direction from north-northeast (010°) within the southern domain to a northeast (030°) transport across the transition hinge and into the northern domain of the Cantabrian Thrust Belt. This transport variation within the northern regions of the transition hinge domain would account for the development of large-scale transpressional structures identified along the Genestosa Fault including the Torre de Babia antiformal stack, the Robledo-Cospedal sidewall duplex, and the La Majúa duplex. Positive flower strictures are also observed.

However, the development from an east-west compression phase within the Moscovian (Early Carboniferous) to a north-south compression during oroclinal bending and vertical-axial rotations within the Early Permian is the dominant cause for the development of cross-strike and along-strike discontinuities within the Cantabrian Thrust Belt. Syn-kinematic structures, such as the transition hinge conical fold developed within the Bodon Unit, are produced during this deformation phase resulting in compartmentalisation within its northern and southern limbs during continued translation. This orthogonal change in transport direction results in the reactivation of thrusts within the southern arm of the Cantabria-Asturian Arc, truncating pre-existing structures and creating along-strike structural disparities (e.g., the 'bevelled zone'). Major structures, such as the Léon Fault, are also reactivated producing dominant frontal structures (i.e., the Cueto Negra-Brañillín Window).

Transpressional structures within the northern hinge would have also been tightened and further enhanced during a north-south compression phase during the development of thrust fault curvature along the Somiedo-Correcillas Thrust and interactions within the central conical fold. Later deformation events, such as the Alpidic Orogeny, may have also extenuated structural disparities during further reactivations during north-south compression.

This research therefore highlights that thrust translations which are oblique to pre-existing structures amplify cross-strike discontinues within the pre-thrust template. With continued deformation syn-kinematic discontinuities would be produced. Furthermore, this research indicates that within multiphase geological setting where more than one transport direction is identified, cross-strike discontinuities are also produced as a result of transecting relict structures from previous deformation events or from passive margin formation. Therefore an understanding of a regions geological history is essential before cross-strike discontinuity identification can proceed.

Aim 3: To determine the effect and / or control the pre-thrust template exerts upon cross-strike discontinuity / transverse zone formation.

The pre-thrust template within the Loch Maree Transverse Zone, and on a larger-scale the Somiedo-Correcillas Unit within the Cantabrian Thrust Belt, has a major impact on the production of cross-strike discontinuities and cross-strike linkages within the developing thrust belts. Discontinuities produced during pre-thrust template development determine what structures are presented to the propagating thrust front and in turn, determine what syn-kinematic discontinuities are produced. Severity of pre-thrust template discontinuities will also impact on the amplification of such features into higher thrust sheets as the thrust belt develops further.

Within the Moine and Cantabrian thrust belts, a combination of structural and stratigraphical variations, both internal and external to the allochthon including, sub-décollement basement faults, pre-thrusting deformation of cover strata above basement faults, and along-strike variations in mechanical stratigraphy control alignments of cross-strike linkages, determine subsequent thrust architectures and focus the development of cross-strike discontinuity / transverse zone development.

Within the Loch Maree Transverse Zone, abrupt compartmentalisation either side of the Loch Maree Fault developed during pre-, and post-depositional fault movements control the separate kinematic developments within the northern and southern walls of the Loch Maree Fault, resulting in the incorporation of basement lithologies within the northern wall.

This research shows that relatively small disturbances within the pre-thrust template can lead to significant lateral variations in thrust geometry, especially along long-lived structures such as the Loch Maree Fault, and its related Proterozoic shear zone. However, impacts from cross-strike discontinuities within the pre-thrust template on subsequent architecture diminish in time.

Where abrupt variations in pre-thrust template architecture are observed, greater cross-strike discontinuities are identified, commonly along transverse faults. Furthermore, alternations along-strike between thicker and thinner stratigraphical successions within the pre-thrust template promotes cross-strike discontinuity development. Cross-strike discontinuities observed within the Cantabrian Thrust Belt across the Genestosa Fault, resulting from abrupt stratigraphical thickness variations, are a good example of this. Within the Cantabrian Thrust Belt, along-strike variations in stratigraphical thickness are assisted by laterally discontinuous stratigraphical units, structural highs and along-strike differential developments of extension faults. Conversely, where minor steps are identified (i.e., Doire Dharaich and Leathad Buidhe) or where gradational changes of stratigraphy are observed within fault network and cross-section analyses, small deflections are identified and thrusts preferentially branch along a series of branch-lines rather than develop compartmental transverse faults.

This research therefore indicates that a combination of structural and stratigraphical variations within the pre-thrust template control the subsequent development of cross-strike discontinuities / transverse zones. Abrupt variations produce the most profound architectural variations within transverse zones, whilst minor gradational changes in structure or stratigraphy produce only minor deflections in architecture. Amplifications of cross-strike discontinuities identified within the pre-thrust template would diminish during orogenic development

8.5. Future Work

Although this research has addressed the original aim and set objectives, several important and related research questions remain and several avenues of potential future research could be explored, results from which would complement this study.

Development of a three-dimensional model for the Loch Maree Transverse Zone

A spectrum of transport-parallel and transport-lateral cross-sections have been produced for the Loch Maree Transverse Zone allowing the pseudo-three-dimensional architecture to be determined. Development of a geological model, similar to those produced within the Assynt Culmination for the Traligill Transverse Zone (e.g., Krabbendam & Leslie, 2010; British Geological Survey, 2012), would allow the development of this zone to be further analysed and potentially sequentially restored within a three-dimensional context.

Further application of new thrust ramp methodologies within various fold-thrust settings

Although this methodology was a success in identifying transport-aligned thrust ramps and thrust nucleation, propagation and termination zones, further refinements are needed through applications within more fold-thrust belt settings to bridge the gap between a linear and oroclinal fold-thrust setting. This methodology does add weight to previous techniques used for cross-strike discontinuity / transverse zone identifications, particularly stratigraphical separation diagrams. Applications within active fold-thrust systems are one avenue of exploration, such as the Apennine Thrust Belt, Italy.

Oscillatory foreland / hinterland propagation in fold-thrust belts and basin dynamics

Structural development in fold-and-thrust belts is characterised, and often intensely debated, as being either foreland-, or hinterland-propagating in nature. In some cases, structural domains that show early development as foreland-propagating are characterised by later out-of-sequence, or 'break-back', thrusting (i.e., Loch Maree Transverse Zone) Structural development in the fold-and-thrust belt is broadly contemporaneous with sedimentary basin development (foreland, piggy-back settings etc.) and will be a strong driver in sediment supply and dispersal and / or delivery to the developing sedimentary basin. Future work would aim to:

- Resolve the extent to which the reality for fold-and-thrust belts development is an oscillatory, or pulsatory, switching between foreland-, and hinterland-propagation
- To identify the structures in the frontal part of the system which are the earliest disturbances in the previously stable foreland, e.g., 'ice-breaker' loading of the leading edge that can rotate easy-slip horizons into favourable (gently hinterland-dipping) orientations
- To identify relict structures in the hinterland that map early loading, and superposition of the new active thrusts
- To distinguish those structures that map recurring phases of out-of-sequence thrust or fault development

- Assess the relative balance between low-angle and steep structures that accommodate strain

8.6. Summary

This study has examined the detailed three-dimensional architecture of, and linkages across, cross-strike discontinuities / transverse zones within the Moine and Cantabrian thrust belts. The development of structural disparities within these orogenic belts is varied. Within the Moine Thrust Belt, the Loch Maree Transverse Zone is formed by abrupt variations within the pre-thrust template which are exacerbated by pre- and post-depositional fault movements along the Loch Maree Fault. Thrust translation obliquity within the Loch Maree Fault northern wall further enhanced cross-strike disparities. Cross-strike discontinuities are also identified within the Cantabrian Thrust Belt.

Cross-strike discontinuities produced within the Cantabrian Thrust Belt are not solely linked to one parental structure, but the thrust belt as a whole. Oroclinal bending focused within the south-western hinge of the Cantabria-Asturian Arc produces a large conical fold along which deformations are compartmentalised producing a transverse zone. Structural disparities are produced within the northern and southern hinges of this fold as a result of localised transpression, alternations of thrust translation direction and the reactivation and / or truncation of pre-existing structures developed during earlier phases of deformation. This research highlights that cross-strike discontinuities / transverse zones represent important syn-kinematic components of thrust belt evolution. Identifications and analysis of cross-strike discontinuities / transverse zones permit understanding of how pre, and / or syn-kinematic structures and stratigraphical variations affect the syn-kinematic plan of the thrust belt as a whole.

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